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VELOPHARYNGEAL FUNCTION
IN CONNECTED SPEECH

STUDIES USING TOMOGRAPHY AND CINERADIOGRAPHY
SYNCHRONIZED WITH SPEECH SPECTROGRAPHY

BY

LARS BJÖRK

~~STOCKHOLM~~

1961

This volume which forms
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Introduction

The methods available for assessing normal and pathological speech have been subjective to a very large extent. Especially in operated cleft palate cases various methods for more objective assessment of speech results have been tried. However they have all been of limited value. The authors have tried to study speech objectively using a roentgen image intensifier and cineradiography. It was soon obvious that studies of cineradiographic films alone were insufficient. It is necessary at the same time to record the speech and have a device for synchronizing it with roentgen cinefilms. The problem of synchronizing cinefilms with speech was solved following contact with the Speech Transmission Laboratory, Division of Telegraphy-Telephony at the Royal Institute of Technology in Stockholm. Simultaneously a sound spectrogram of the connected speech was obtained. It was possible to make a detailed analysis of the speech from these spectrograms.

The method developed is suitable for studies of the anatomy and physiology of the speech organs during normal connected speech. Such studies are of great value in analysis and synthesis of speech and are necessary as a basis for assessment of therapeutic results in pathological cases.

It has long been known that velopharyngeal closure is of very great importance in the production of normal speech. Since our starting point was the restitution of normal velopharyngeal closure in cleft palate cases, we decided in this investigation to limit our studies to the function of the soft palate and the velopharyngeal closure.

Chapter I describes the methods developed for synchronized cineradiographic and sound spectrographic studies of connected speech.

In Chapter II studies of the reliability of the methods are found.

Chapter III contains tomographic studies of the anatomy and physiology of the velopharynx and Chapter IV cineradiographic and sound spectrographic studies in normal subjects.

The methods described in Chapter I were developed in cooperation with Dr. BENGT NYLÉN.

Studies in cleft palate patients with our methods are published by NYLÉN in *Acta radiologica* 1961, suppl. 203.

CHAPTER I

Methods

Speech and its physiology have long been the objects of intensive study. At an early stage it was found that the soft palate and its function were of great importance in speech. The possibilities of studying its function by direct inspection of the palate via the mouth are naturally limited. It has only been possible to observe the movements of the soft palate in special cases where defects in the face following tumours, operations, etc. have existed.

In 1836 HILTON was one of the first to report a case of a "large bony tumour in the face completely removed by spontaneous separation" after which he made observations of some of the functions of the soft palate through the hole in the face. Since then and up to the present time, there have been a number of similar observations of the soft palate and pharynx at rest, during speech and swallowing. As a result, knowledge of the function of the soft palate has increased.

SCHEIER in 1897, introduced a new procedure for visualizing the speech mechanism using roentgen rays. Many similar reports followed his publication and to-day, roentgen rays are widely used for this purpose. During the last 30 years cephalometry has been developed and has become most important, while tomography has also provided valuable information in this research field.

Single roentgen pictures have obvious limitations. A picture can be taken only during sustained speech sounds with the speech organs immobile. This picture provides only a fraction of the positions and movements of the speech organs during the production of sound.

For the physiological study of connected speech, cineradiography is necessary. In cineradiographic studies of the soft palate CARROL (1952) was able to reduce the radiation effect by synchronizing the roentgen generator and the shutter of the camera. He took 15 frames per sec. and the radiation effect during 6 secs. did not exceed 18 r. He concluded that the application of cineradiography could be of routine diagnostic help in stating the function of velopharyngeal closure and also the effects following operation.

With the development of the roentgen image intensifier, high speed cineradiography has been made possible without exposing the patient to excessive roentgen dosage. Employing this method many experimental and clinical observations have been made of different organs such as the heart, lungs, circulation

and functions such as tubar motility and swallowing. Only a few reports have been published about the function of the soft palate. Using cineradiography, ARDRAN & KEMP (1951-1956) studied swallowing, but also made some observations on velar function. CALNAN (1958) together with the latter authors, studied four cases of submucous clefts, using the image amplifier and has also made further use of this technique in cleft palate speech studies. COOPER & HOFFMAN (1955), NYLÉN & SKOOG (1955), NYLÉN (1957), CONWAY & STARK (1957), and CROATTO & CROATTO-MARTINELLI (1959) have all used the image intensifier in studies of the soft palate during speech in cleft palate cases.

COOPER (1956) and MILLARD (1957) combined the use of cineradiography with sound spectrography as an aid in cleft palate studies, while TRUBY (1959) studied consonant articulation in normals, using this combination.

All the authors mentioned above consider cineradiography of great value in studies of the speech organs. However they did not make any attempts at a more objective and detailed analysis of the cinefilms obtained and they had no method for exact synchronization of high speed roentgen cinefilms of the speech organs with the sound produced.

Recently MOLL (1960) reported a pilot study of cineradiographic sound analysis. He used a 24 frame per second sound film camera and studied two sustained vowel sounds and six disyllables in two adult females. He analysed the film frame by frame and identified the frames by visual inspection of the variable area sound track. He also studied the frequency variation of the second formant of the vowels.

From this review it is evident that cineradiographic analysis of connected speech has not been performed. The main reason for this is that no practical method has been available for exact synchronization of the roentgen film with the sound produced. The large amount of work required may also have diminished the interest in analysis of this type.

We have used speech spectrograms synchronized with cineradiographic films. Synchronization has enabled us to relate every single frame of the cinefilm exactly to the speech sound via the spectrogram.

This part of the thesis presents the use of our method for examining the physiology of the soft palate during connected speech by means of synchronized cineradiography and sound spectrography.

1. Apparatus

The roentgen cinefilm was taken with a 5" Philips image intensifier with accompanying 35 mm. Arriflex film camera. (Fig. 1 A.) A four valve roentgen apparatus with a smoothing capacitor was used. The tube used was a Siemens Pantix with 0.3×0.3 mm. and 1.2×1.2 mm. focus. Total filtration 2 mm. Al.

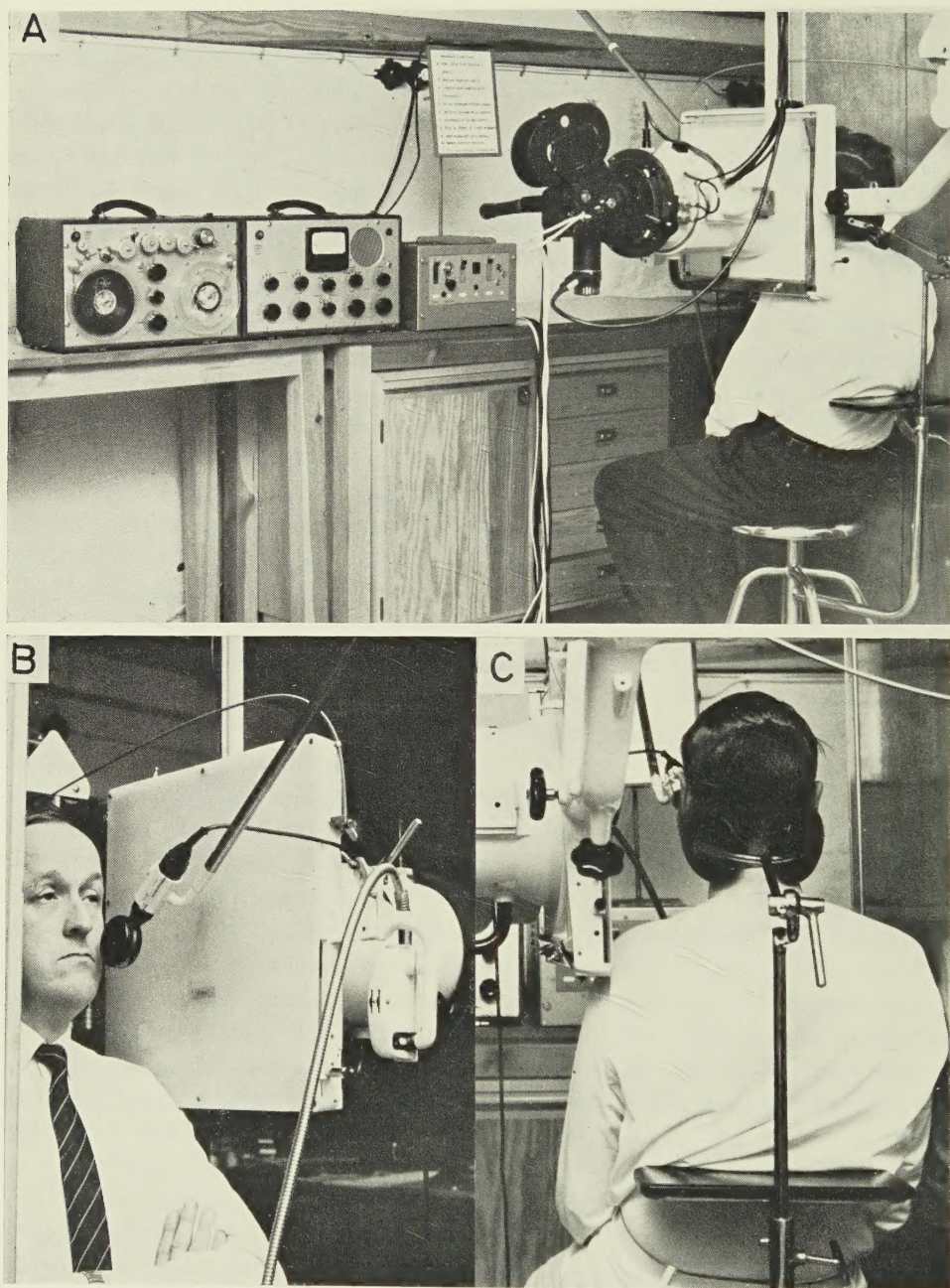


Fig. 1. A. Apparatus used. From left: Lyrec high-fidelity twin-track tape recorder, synchronizing device, above which the board with the test sentences to be read, the Arriflex 35 mm. film camera, with Philips 5" image intensifier.
B. position of the microphone in relation to the mouth of the test subject.
C. The head of the test subject against the head-rest.



Fig. 2. Viewer for analysis of 35 mm. roentgen cinefilm. The film can be projected with a speed of 0 to 50 frames/sec. Tracings of individual frames are made on the translucent screen. The automatic counter next to the observers left hand makes it possible to find any particular frame of the cinefilm.

The exposure data were 85–95 kV at 2–4 mA. No secondary grid was used. The film was Gevaerts Scopix G and was developed for six minutes at 20° in G 230 or at a commercial laboratory with the usual procedure for negative film. The developing time was however increased from three to five minutes.

The developed roentgen film was analysed in a Philips viewer (Fig. 2) in which the film is projected on to a translucent screen. In this viewer the film can be projected frame by frame or continuously at any desired speed up to 50 frames/second. The film can be run both forwards and backwards in this projector. An automatic counter makes it possible to find any particular frame of the cinefilm.

The sound was picked up by a velocity type microphone (Sennheisser type MD 3) (Fig. 1 B). The sensitivity of the microphone decreases much faster with

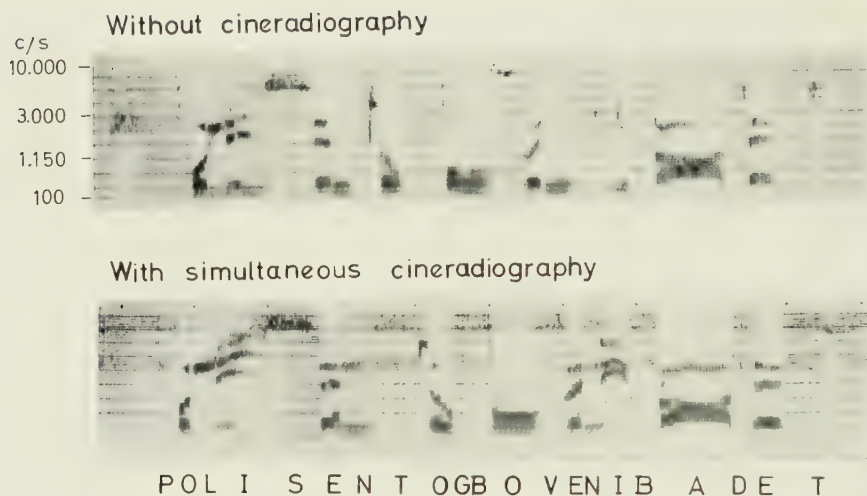


Fig. 3. Sund spectrograms from recordings of the same test sentence—*pu'li:sən tu:g 'bu:vən i 'bɑ:dət* (The policeman caught the villain in the bath)—without and with simultaneous cineradiography. The synchronization marks are seen as small black dots at the upper border of the latter spectrogram. The noise from the filmcamera is seen as disturbances located mainly in the frequency range above 800 c/s.

distance than in an ordinary microphone. With this type of microphone, the disadvantage of disturbing noise from the roentgen and film apparatus can be largely reduced. Speech was recorded on one track of a twin-track Lyrec high-fidelity tape recorder (Fig. 1 A). The speech was later analysed by a sound spectrograph (visible speech method) which gives a continuous spectrum picture on 35 mm. film. The time axis is the long axis of the film, and the frequency scale 50–10,000 cycles/second, at right angles to it. The intensity of the spectral component is expressed by the degree of blackening (Fig. 3). This spectrograph was constructed by SUND (1957) and consists of 48 fixed bandpass filters and the filter outputs—after rectifying and smoothing—are scanned 500 times per second by an electronic commutating switch. The 49th channel is used for synchronization marks. With this method, analysis of long periods of speech and synchronization between the sound spectrogram and film become practical procedures.

This synchronization is obtained by means of a special mechanism, connected to the driving shaft of the film camera. A marking signal is given for every frame of the cinefilm. This marking signal is recorded on the second track of the Lyrec tape recorder. Every tenth marking pulse is amplified and, in addition, a marking of the corresponding frame of the film is made by means of a



Fig. 4. Twelve consecutive frames from a roentgen cinefilm. At the edge of every tenth frame is the black synchronization mark.

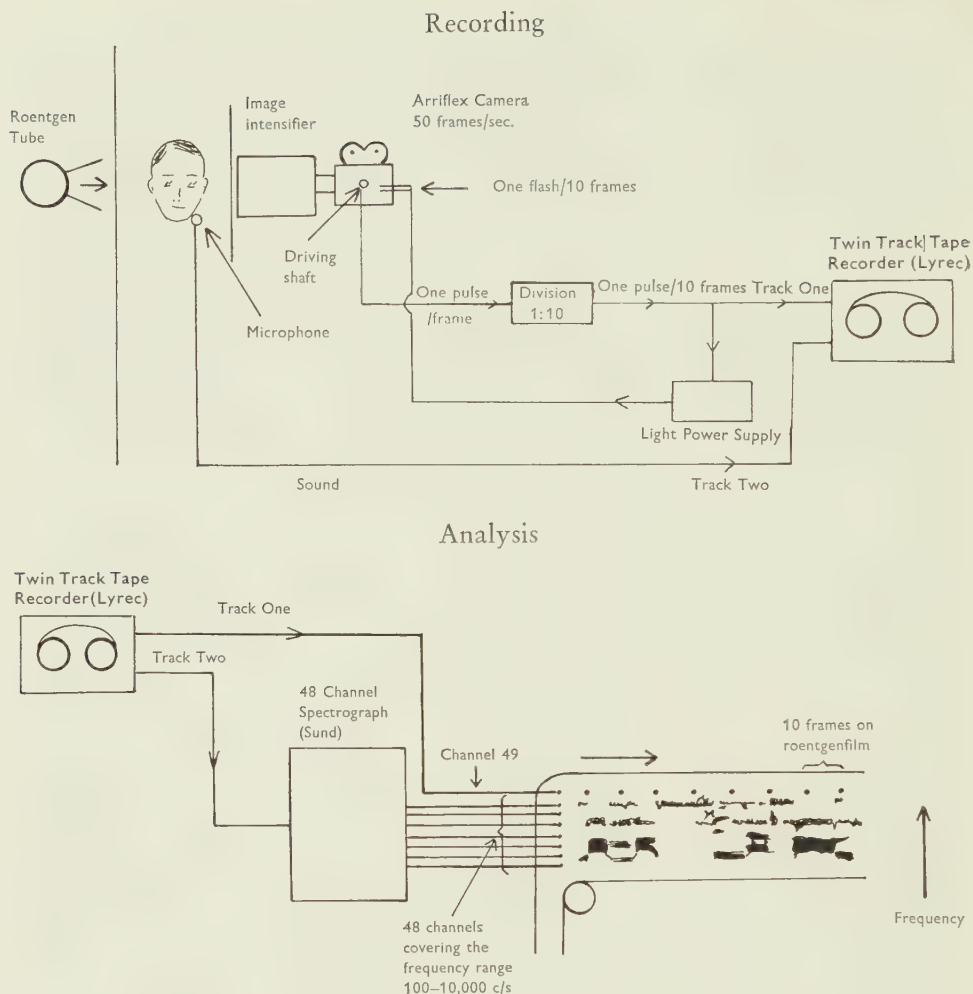


Fig. 5. Diagram showing the principles of the system used for synchronizing roentgen cinefilm with the speech produced.

blackening at the edge of the frame (Fig. 4). These black marks on the roentgen cinefilm corresponding in time to the larger pulses on the magnetic tape are numbered serially by using the counter in the viewer.

At the upper border of the spectrogram obtained using Sund's spectrograph are the larger synchronizing pulses for every tenth frame recorded. These marks are numbered serially in exactly the same way as the corresponding marks on the roentgen cinefilms. (Fig. 3.)

By this means, the spectrogram and cinefilm can be exactly synchronized with ease.

This synchronizing device was constructed by Aage Møller at the Speech Transmission Laboratory, Division of Telegraphy Telephony, Royal Institute of technology, Stockholm. The principles of the construction can be seen in Fig. 5. The synchronizing device can also be used for synchronizing cinefilms with the recordings of ECG, bloodpressure etc.

For studies of certain details of the speech produced, another spectrograph, the Kay Electric Sonagraph, was used.

For more detailed description of visible speech and spectrography, reference should be made to POTTER, KOPP & GREEN (1947), SUND (1957) and FANT (1958).

2. Methods of investigation

The subject for examination was seated upright with the head against a head-rest. (Fig. 1 C.) No other apparatus for fixation (earplugs etc.) was applied to the head. The microphone was put just in front of and a little to one side of the subject's mouth. (Fig. 1 B.) Using the image intensifier, the position of the head was checked in order to obtain as straight a lateral projection of the soft palate as possible. The picture field was adjusted to take in the speech organs from the glottis to the lips where the patient's size and the relatively small field allowed. The films were taken with a frequency of about 50 frames/second for periods of approximately 15–20 seconds. In order to make measurements easily on the roentgen film, without considering the enlargement factor, a metal ruler was placed along the midline of the mouth of every patient for about half a second at the beginning of filming.

In three adults and three children, the roentgen dose on the skin on the side of the neck facing the roentgen tube was measured, using the method described by LARSSON (1958) and was found to be between 1.5 and 2 r for a complete investigation of this type. (LARSSON 1960.) The gonads received no measurable roentgen dose.

The following test sentences were read by the experimental subject/patient during the cineradiographic-spectrographic recording. The phonetic transcription largely agrees with the illustration in *The Principles of the International Phonetic Association* (1949, reprinted 1960).

1. Mammas fina schal
 $\sim$ mammas $\sim$ fi:na fa:l
 Mummy's fine shawl
2. Polisen tog boven i badet
 pu'li:sən tu:g 'bu:vən i 'ba:dət
 The policeman caught the villain in the bath

3. Gatan var hal av is
ˈga:tan va ha:l a:v i:s
 The street was slippery with ice
4. Ingen var vaken vid midnatt
ˈiŋŋən va ˈva:kən vi:d ˈmi:dnat
 No one was awake at midnight

In some cases there was time during filming to read a few more sentences, but this was exceptional. Immediately after the roentgen filming the experimental subject/patient repeated these four sentences and then continued as follows:

5. Kicki kokar potatismos
ˈkiki ˈku:kar puˈta:ti:s mu:s
 Kicki cooks mashed potatoes
6. Geten jagade killingen
ˈje:ten ˈja:gade ˈçiliŋən
 The goat chased the kid
7. Pappas vita skjorta
ˈpappas ˈvi:ta ˈfu:ʃa
 Daddy's white shirt
8. Tjo å tjim å inge annat
çu: ɔ çim ɔ ˈiŋŋə annat
 Ding! Dong! and nothing else!
9. Var noga vid val av bil
va ˈnu:ga vi:d va:l a:v bi:l
 Be careful when choosing a car
10. Mimmi bakar kakor
ˈmimmi ˈba:kar ˈka:kur
 Mimmi bakes biscuits
11. Fick du fikon Zackarias?
fik də ˈfi:kən sakaˈri:as
 Did you get a fig, Zacharias?

On the spectrogram from this second recording, details could be more easily identified than on the spectrogram from the recording disturbed by the noise of the film camera. (Fig. 3.) This second recording was also used for the listening test. (Chap. IV, p. 44.)

During examination of children unable to read, the examiner read the sentences or words aloud and the children were asked to repeat them after him.

From the speech recorded during and just after filming, two types of spectrogram were made using Sund's spectrograph. First the ordinary spectrogram covering the whole frequency range from 50–10,000 c/s was made followed

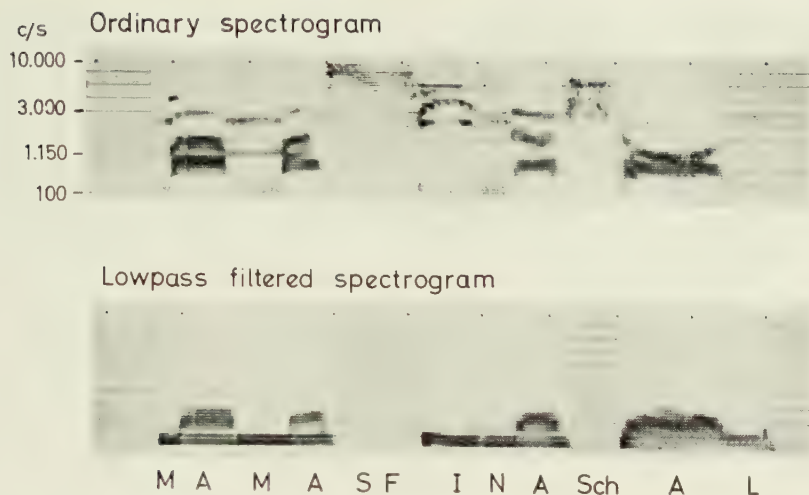


Fig. 6. Sund spectrograms from a sound recording during simultaneous cine-filming. In the lowpass spectrogram the weak M, N, and L are much more easily identified than in the ordinary spectrogram from the same recording. Test sentence *ˈmamməs ˈfi:nə ʃa:l* (Mummy's fine shawl).

by a spectrogram of low pass filtered speech. (Fig. 6.) This latter spectrogram was used as a complement to the normal spectrogram for determination of the time for beginning and ending of weak voiced periods.

The continuous spectrogram of the recorded speech was then analysed. The beginning and end of speech can be determined as well as the duration of sound and silent periods. Every fraction of the individual sounds can be correlated exactly with the corresponding picture frame. The time axis of the spectrogram had an error of less than 1 % (MØLLER 1960).

The roentgen film was analysed in the viewer, both frame by frame and with the film running at different speeds. The resting position of the soft palate and the characteristic positions of closure were drawn directly on to drawing plastic from the translucent screen of the viewer. Similarly, tracings were made of the posterior part of the tongue, the posterior wall of the pharynx and the hard palate as far as the anterior nasal spine. The numbers of the frames on which a movement began and ended were noted and tracings were made of those frames. The pictures obtained from these tracings were then measured and the lengths of the hard and soft palates, the area of the posterior pharyngeal wall covered by the soft palate during closure, and the total movement of the soft palate were determined. (See Chap. IV, p. 47.) In some cases the minimal distance between the soft palate and the posterior pharyngeal wall was measured directly on the screen frame by frame.

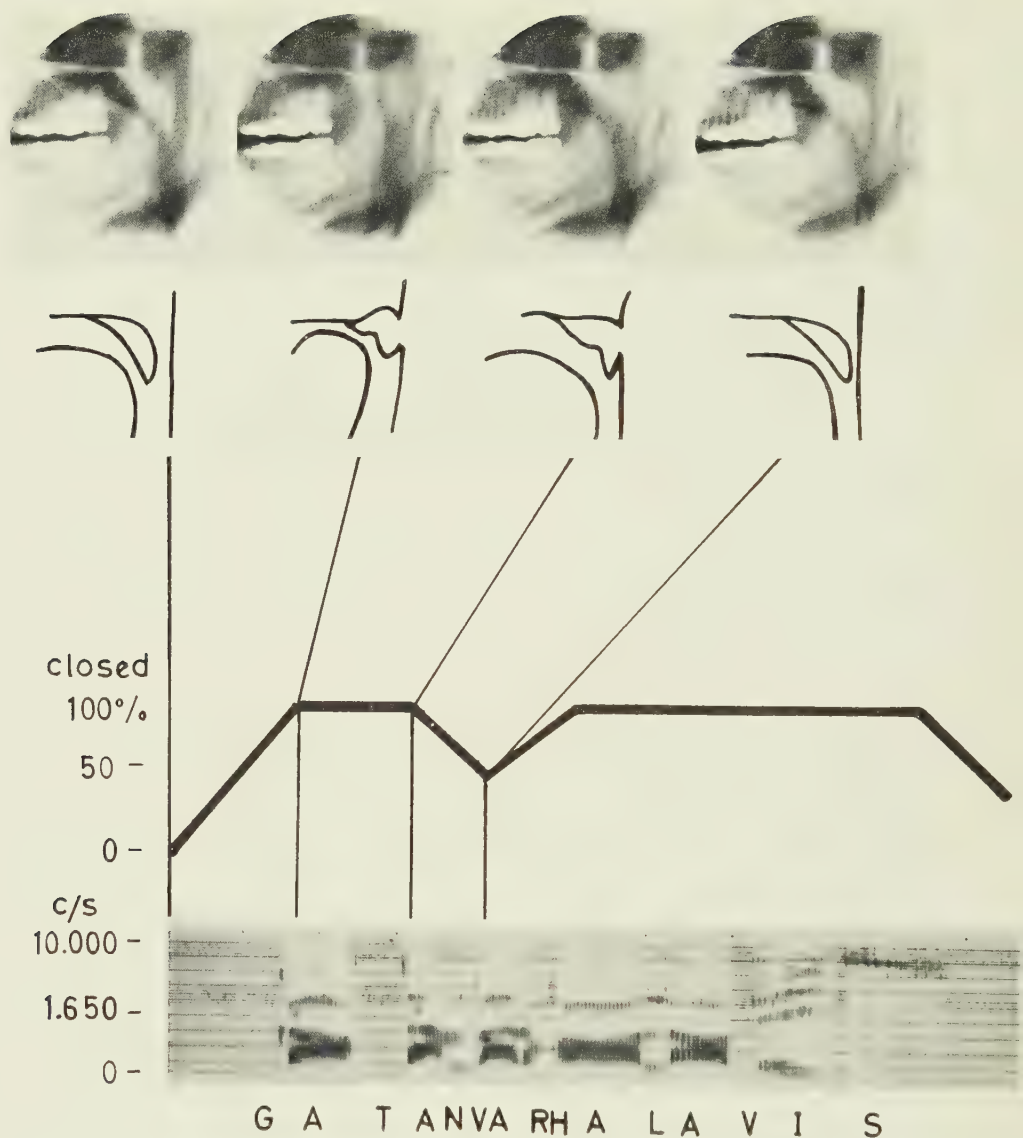


Fig. 7. Synchronization of speech spectrogram with the roentgen cinefilm. From below: 1) Sund spectrogram of the test sentence *gā:tan vā hā:l ā:v i:s* (The street was slippery with ice). Synchronization marks are visible at the upper border. 2) Diagram of the movements of the soft palate during pronunciation of the test sentence. The diagram and the spectrogram are exactly correlated with each other in time. Thus the connected speech as seen on the spectrogram can be correlated with the movement or position of the soft palate. 3) Selected frames from the cinefilm (with tracings) display the movements of the soft palate.

The information from analysis of the roentgen cinefilm and the spectrogram was then assembled in the form of diagrams. (Fig. 7.)

In these diagrams the time axis is horizontal reading from left to right. The positions of the soft palate are plotted along the vertical axis. On the horizontal axis the soft palate is fully open in "rest position". A completely closed position of the soft palate is indicated as 100 %. The positions between those two represent different degrees of opening between the soft palate and the posterior wall of the pharynx. With the aid of the synchronizing marks the speech spectrogram is put exactly in place under the diagram of the movement of the soft palate. (Fig. 7.) It is then possible to record the position and movements of the soft palate during each individual sound. From these diagrams it is also possible to measure how long before the actual production of any sound the movements of the soft palate begin. The mean speed of the movements of the soft palate for different group of sounds can also be calculated.

On the spectrogram were marked where the movement of the palate began and ended, where the palate was maximally opened and where it had returned to the closed position as shown by the synchronized roentgen cinefilm. In this way changes in the spectrogram in relation to the movements of the soft palate have been observed.

The voiced sounds have mostly been investigated (voice speech sounds are sounds where the vocal cords are vibrating: vowels and voiced consonants).

In some cases a more detailed analysis was carried out in which the frequency and intensity of the different formants were determined. (Energy maxima in the speech spectrum are called formants. The frequency of a formant is the frequency at which the spectrum envelope is maximum. Formants are usually named F_1 , F_2 , F_3 where F_1 has the lowest frequency. (Fig. 8 B, C.) The amplitude in dB of a formant is named L_1 , L_2 , L_3 In normal speech the vowels and voiced consonants can be almost exclusively characterised by the frequency of these energy maxima.)

By means of the Kay Electric Sonograph a spectrogram—visible speech—has been produced (Fig. 8 A) and a so-called cross section analysis of certain vowels has been performed. (Fig. 8 B and C.) A "cross section" also referred to as a "section" is a spectral diagram which shows amplitude versus frequency in a selected time.

This analysis has been carried out with a "wide-band", analysing filter (width 300 c/s) and with a narrow-band filter (width 45 c/s) (Fig. 8 B and C). The integration time was 6 msec. In the narrow-band sections obtained, the formant frequency was determined by drawing a smooth curve through the peaks (partial tones) in the diagram, attempting to approximate the so-called envelope. The frequency of the first and second formants, F_1 and F_2 , have been determined and usually also the third and fourth F_3 and F_4 (Fig. 8 B and C).

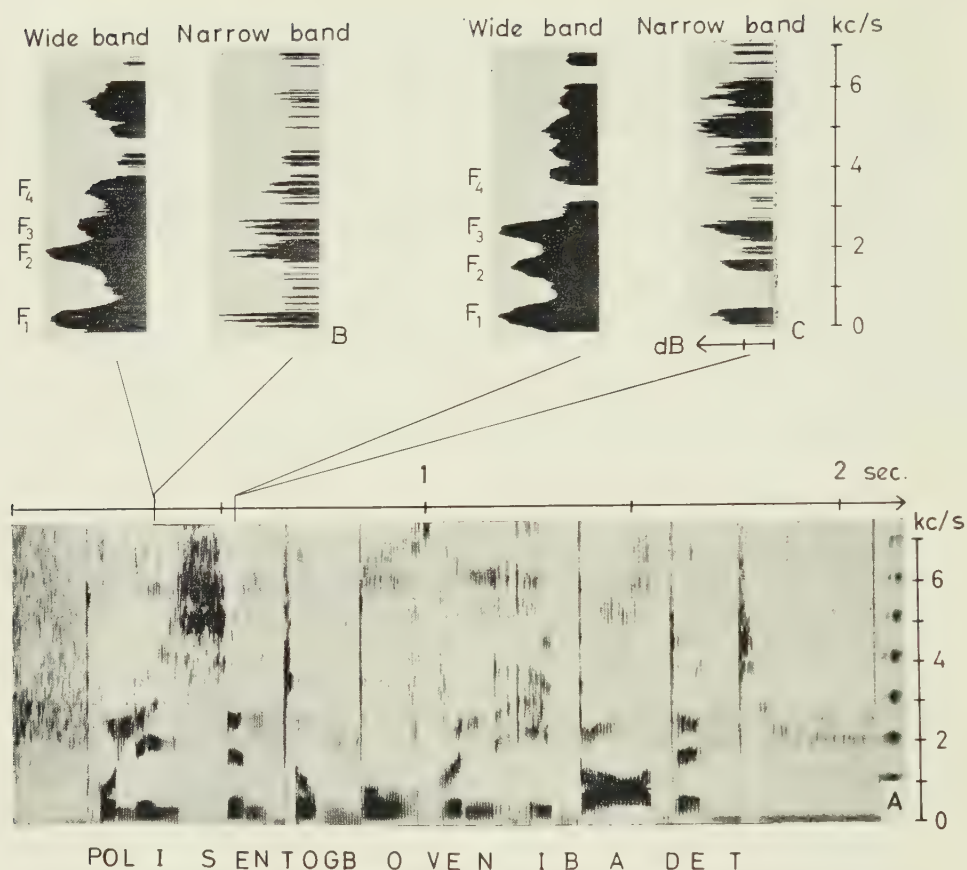


Fig. 8. A. Spectrogram obtained with the Kay Electric Sonograf. Test sentence *pu'lɪ:sən tu:g 'bu:vən i 'bɑ:dət* (The policeman caught the villain in the bath). This spectrogram—visible speech—shows frequency along the y-axis and time along the x-axis. Intensity is proportional to the degree of blackness. The disturbances from the filmcamera are most evident at the left edge of the visible speech.

B. Spectrogram—section—of the vowel [i] that shows intensity versus frequency in a selected time. The intensity maxima are called formants F₁, F₂, F₃, F₄. Both "wide band" filter (width 300 c/s) and "narrow band" filter (width 45 c/s) are used.

C. Spectrogram—section—of the vowel [ə].

In addition the fundamental pitch F_0 was determined. (F_0 is the frequency of the vibration of the vocal cords which is equal to the distance between the partial tones in the spectrum.) The amplitudes L (height) of the envelope at the formant frequency were measured and their values in dB relative to an arbitrary reference were calculated (formant intensity). The ratio of formant intensities L_1 , L_2 and L_3 were calculated (by using the logarithmic measure dB,

the ratio was obtained by subtracting dB values). In some abnormal cases where it was impossible to determine the frequency of the second formant, the intensity was measured at the likely formant frequency, obtained by using the formant frequency values given by FANT (1959).

Determination of formant frequency from spectrum analysis is difficult and sometimes nearly impossible for female and children voices because of the high fundamental pitch which makes the spectrum contain only few partial tones with great distance between. This makes it difficult to determine the envelope and with that the formant frequency.

3. Comments on apparatus and methods of investigation

During this investigation roentgen exposure was continuous during filming. It would have been valuable to have had a device whereby roentgen exposure only occurred during the actual exposure of each frame of the cinefilm as described by ASTLEY (1955), ABRAHAMS (1959) etc. The roentgen dose received by the patient would be less and also the risk of overheating of the roentgen tube during long periods of filming would be reduced. There was no possibility of obtaining such a device with a picture frequency of 50/second at the time that this investigation was planned and begun. The exposure factors used with relatively high kV and very low mA were chosen to reduce the roentgen dose for patients and experimental subjects as much as possible.

The resolving power in the roentgen cinefilms obtained is considerably less than in conventional roentgen films. The resolving power with our apparatus and film (Gevaert Scopix), according to FEDDEMA (1959) is 12.5 lines/cm. The diameter of the smallest metal wire which can be distinguished is 0.4 mm. The depth and diameter of the smallest distinguishable hole in a plexiglass phantom is 2 mm.

However, studies on a plexiglass phantom of the space between the soft palate and the posterior pharyngeal wall (see Chap. II, p. 23) show that a space with a sagittal width of 0.5 mm and a frontal depth of 5 mm can easily be seen.

This resolving power is largely determined by factors dependent on the construction of the image intensifier. According to FEDDEMA, the use of a very fine-grain film only improves the resolving power 10–15 %. A similar fine-grain slow film requires much too high exposure per frame to be of use with a frequency of 50/sec. as in this investigation.

We have attempted coating the surface of the velopharyngeal mucous membrane with contrast medium as described by CALNAN (1958), CROATTO & CROATTO-MARTINELLI (1959) etc. In our experience this procedure does not give any advantages and indeed in some cases some of the structures are difficult to identify. However if one is interested in the lips and anterior parts

of the tongue, marking of the midline with contrast medium in these structures is of value and facilitates identification.

The frame frequency of 50/sec. used, was the highest possible with our camera. In the majority of cases, this frequency was constant, but sometimes it was slower, the minimal value being 43/sec. The camera sometimes even varied in frequency during one and the same filming session, but these variations were usually small. Attempts were made at keeping the camera at a constant speed by using centrifugally governed or synchronous motors, but they had a much too long acceleration time. About a half of the contents of the film cassette were wasted before the camera reached the desired constant speed of 50 frames/sec. On this account, the available motors could not, in fact, be used. All determinations of time were made from the spectrograms obtained with the Sund spectrograph. Since Lyrec tape recorders and the Sund spectrograph have a very constant speed the error in the spectrogram time axis is less than 1 % (MØLLER 1960). As determinations of time were made from the spectrogram and synchronization marks appear on both spectrogram and film, changes in film camera speed are always discovered. When the camera has been running with the desired speed of 50 frames/sec. the connections between and synchronization of the spectrogram and film are very simple. The continuous spectrogram runs with a speed of 50 mm/sec. Under these circumstances 1 mm. corresponds to one frame on the film. When the camera varied in speed or had another speed than 50/sec., it has been necessary to correct for this in the calculations.

The frame frequency of 50/sec. was sufficient to detect all the movements of the soft palate. This conclusion may be drawn since no paradoxical sequence of movements was found. However it is obvious that extreme positions of the soft palate in conjunction with a rapid opening movement, immediately followed by velopharyngeal closure could have been missed. The maximal opening position of the soft palate could have been as much as 1–2 mm. lower than that seen on the film.

With a frame frequency of 50/sec., the exposure time for every frame is 1/150 sec., i.e. a little less than 0.007 sec. We have noticed that the palate in some instances moves as much as 3 mm. between two frames. (Fig. 9.) This means that the soft palate can move 1 mm. during the actual exposure time of the frame. This produces a blur which of course with moving projection of the film is not noticed, but tracing of the frame in question during still projection may be difficult. In some apparatuses e.g. Philips 11" image intensifier, a camera is used with a shutter sector greater than 120°. In this way it is possible to prolong the exposure time of each time and thus reduce the roentgen dose for the patient. However, such a camera would have been unsuitable for an investigation of a rapid sequence such as the movements of the soft palate.

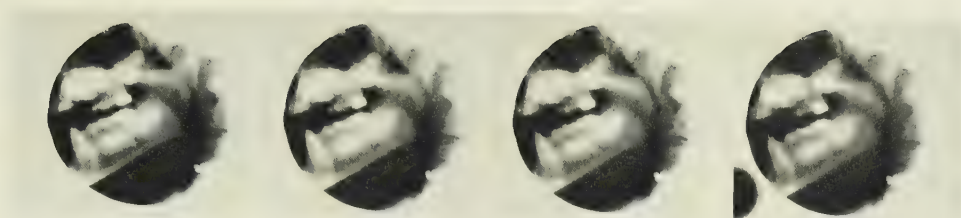


Fig. 9. Four consecutive frames from a roentgen cinefilm taken at a speed of 50 frames/sec. The rapid opening movement of the soft palate is clearly seen.

Study of the movements of the soft palate was carried out with the patient sitting and in lateral projection only. Of course, another projection, either frontal or semiaxial would have been valuable for study of velopharyngeal closure and the speech organs in general. A better three-dimensional conception of the movements and more exact measurements of cross-sectional areas at different levels in the speech organs could be obtained. However, attempts at producing acceptable cinefilms in the frontal or semiaxial projection, using the apparatus described, have been unsuccessful. Due to the complicated shape of the speech organs and the numerous disturbing skeletal shadows, the assessment of the films in these projections is impossible or very uncertain.

Studies of how accurately velopharyngeal closure can be assessed with roentgen cinefilms in lateral projection only can be found in Chap. III, p. 34.

In our experience, patients and experimental subjects find it difficult to relax and use their ordinary voices if the head is too rigidly fixed during filming. This is especially so with children, who have greater difficulty than adults in speaking normally under these circumstances, unless they have plenty of time to get used to the apparatus. FANT and others have also pointed out the disadvantages of too great fixation of the head. The disadvantages of using only a simple head-rest as ours is, of course, that the patient can turn the head to such an extent that assessment of the films is made difficult or impossible. Studies of the significance of possible oblique projections are to be found in Chap. II, p. 25.

As a rule the person to be examined has been able to read four of the test sentences during the 15–20 seconds of filming. During that time 750–1000 frames have been taken and the soft palate has performed about 25 closing and opening movements. We consider the data collected during that time sufficient for this study of the velopharyngeal closure.

By thus limiting the time for each examination we have been able to keep the amount of work necessary for analysis of each film within reasonable limits.

In order to produce spectrograms suitable for analysis, it is very important to obtain a recording of the sound produced of as high a quality and as free

from disturbances as possible. Disturbing sounds are produced mainly by the film camera and to a lesser extent by the roentgen apparatus. The use of a conventional microphone for sound recording was not possible. The sound produced by the experimental subject was completely masked by disturbances mainly due to the film camera. It has been possible to improve the signal-noise ratio very greatly, by using the special Sennheisser MD3 velocity-type microphone. It has a powerful noise-reducing effect due to a very rapid fall in sensitivity with increased distance from the sound source. The substitution of plastic materials for plywood in some parts of the roentgen apparatus was also of value in improving the signal-noise ratio. The disturbing noise occurred mainly in the frequency range above 800 c/s. It activated the automatic gain control in the spectrograph and thus also caused suppression of the lower frequencies. However by using a spectrogram of low pass filtered speech from the synchronized sound-film recording it was possible to identify certain sounds more easily due to attenuation of the frequencies above 400 c/s in these low pass filtered spectrograms. (Fig. 6.) Furthermore we have been able to identify details in the spectrogram relating to disturbances or to the produced speech by making a speech recording only immediately after the synchronized film and sound recording. We consider the above procedures satisfactory for the present investigation. A further improvement of signal-noise ratio can be thought desirable in continued studies of this type. Such an improvement can be produced by e.g. padding the film camera and using a microphone with an even more powerful noise-reducing effect than we have used.

The synchronising device has functioned very satisfactorily and in the great majority of cases has produced a mark on every tenth frame. In a few cases however the marks have come on every ninth or eighth frame. Even during recording of one and the same film, small irregularities have sometimes appeared, so that at a particular point the distance between two marks has been only 8-9 frames. However these small irregularities in functions do not affect the reliability of the synchronization system and may be used as an extra check of the correctness of the synchronization. The distance between the recording heads in the Lyrec-apparatus which was used for recording of sound in conjunction with filming and in the Lyrec apparatus used with production of the spectrograms have been measured and found to be exactly similar. Thus no deviation in time could have been due to such an error. Synchronizing pulses are given about 45° after the maximal shutter opening of the film camera. The delay in time thus produced amounts to only 2 msec. and has no practical importance.

CHAPTER II

Studies on the Reliability of the Methods

In addition to the comments on apparatus and methods of investigation in Chap. I, a number of studies to evaluate the reliability of the methods used are presented in the following.

Tomographic methods were used in the study of some of these problems. The tomographic technique was also used in studies of variations in the coupling area between the nasal and oral cavities in normal subjects. The tomographic studies have therefore been combined in one chapter.

1. Experiments with a plexiglass phantom to determine
the resolving power in the image intensifier
—Arriflex camera—Scopix G-film system used

As a result of the tomographical investigations of the anatomy in the velopharynx during closure (Chap. III, p. 40), it has been found that the space between the soft palate and the posterior pharyngeal wall to be reproduced is 10 mm. long in the frontal plane when it is about 1 mm. wide. As closure continues both the depth and the breadth of the space diminish. The aim of this experiment was to study in a plexiglass phantom how small a space could be observed between two soft tissue structures with the apparatus used in this investigation.

The phantom used consisted of a plexiglass cube with a side of 7 cm. Small spaces were cut out of the centre. Three of these airfilled spaces had a depth of 5 mm., while three had a depth of 10 mm. In each of these two groups the spaces were 1/2, 1 and 2 mm. wide. The distance between the spaces was 3 mm. Fig. 10.

The phantom was placed in a way corresponding to the subject's velopharyngeal region in the investigations previously described by us. Using the technique described, a roentgen cinefilm with a frequency of 50 frames/sec. was taken with the 1 mm. space in the centre of the field, in both the 5 mm. deep spaces and 10 mm. deep spaces. In addition, 4 cm. of plexiglass was added to the phantom to give the same density as the neck of an adult subject.



Fig. 10. The plexiglass phantom used to determine the resolving power. Six slits are cut centrally in the plexiglass cube. Three of them are 5 mm. and three are 10 mm. deep. In each group the slits are 2, 1 and 0.5 mm. wide.

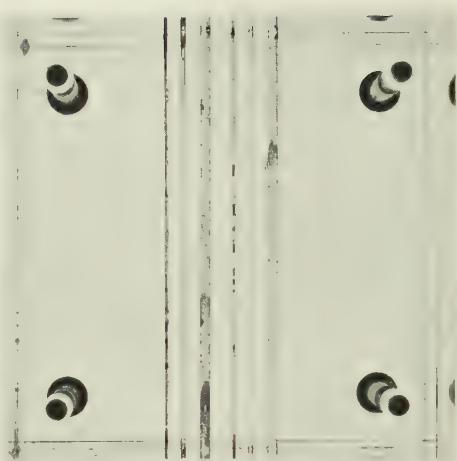
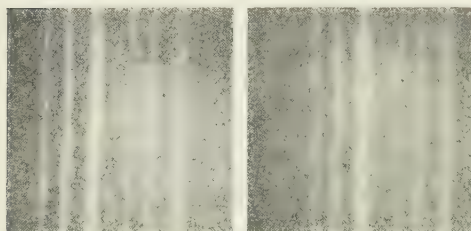


Fig. 11. Cineradiographic frames of the plexiglass phantom. In the left picture the central beam is parallel with the slits. In the right picture there is an angle of 10° between the slits and the central beam. In both pictures the smallest slit in the phantom, 0.5 mm. wide, 5 mm. deep, is clearly seen.



When the film was viewed, even the smallest cavity, 5 mm. deep and 0.5 mm. wide could be distinguished. Fig. 11.

The plexiglass phantom corresponds approximately to the soft tissues of the velopharynx, i.e. the soft palate, the posterior pharyngeal wall and the space between. It is thus possible to conclude from this experiment that even a space 5 mm. deep and 0.5 mm. wide between the soft palate and the posterior pharyngeal wall can definitely be reproduced and observed on roentgen cinefilm. Of course the boundary between air and soft tissue structures in the velopharynx are not so sharp and well-defined as the plexiglass-air boundary in the phantom. The possibilities of seeing a small cavity between the soft palate and the pharyngeal wall are therefore not so good as in the phantom experiment. However, our experience has been that very small spaces about 0.5 mm. wide can be observed on cinefilms of the experimental subjects. Thus the accuracy of our assessment of whether or not velopharyngeal closure occurs

is not mainly dependent on the resolving power of the apparatus used. In our experience, other factors are of greater importance, such as blurring caused by rapid movements and interference by e.g. the bony structure of the mandible.

2. The significance of a true lateral projection of the soft palate in the assessment of closure or nonclosure of the velopharynx

In our experience, although spaces between the soft palate and the posterior pharyngeal wall of less than 1 mm. in width can easily be seen, they cannot be measured accurately. In Fig. 12, a space between the posterior pharyngeal wall and the soft palate of 1 mm. has therefore been taken as the minimum which can be measured with certainty.

In the tomographic studies (Chap. III, p. 41), we were able to show that when the distance between the soft palate and the posterior pharyngeal wall is 1 mm. the frontal diameter of the space between these two structures is about 10 mm. In addition, the posterior surface of the soft palate and the posterior pharyngeal wall are largely parallel with each other.

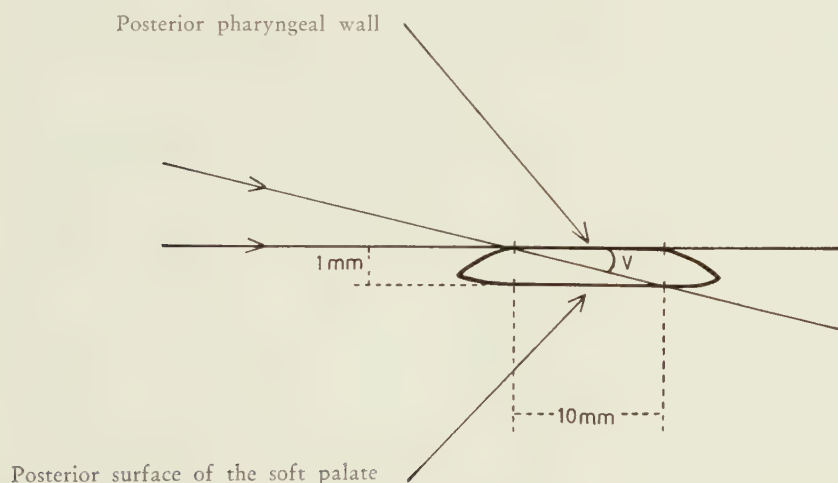


Fig. 12. The ellipsoid figure represents the cross-sectional area of the space between the velum and the posterior pharyngeal wall. If the head is turned v° , a point on tube side of the posterior pharyngeal wall is projected on to the soft palate and there would be difficulties in assessing whether or not there is a velopharyngeal closure. With the dimensions given in the Figure: $\tan v = 1/10$; $v = 6^\circ$.

For this reason the posterior surface of the soft palate and the posterior pharyngeal wall have been drawn parallel to each other for a distance of 10 mm. in Fig 12. In order to project a point on the border of the soft palate, nearest to the roentgen tube, on to the posterior pharyngeal wall, the head must be turned through at least 6° . (See Fig. 12.) If the head is moved this much, it would be difficult to tell whether or not there is a space between the two structures.

To confirm this, the plexiglass phantom of the space in the velopharynx described on p. 24 has been filmed turned 10° from the true lateral projection. Even with this degree of rotation, the spaces are clearly seen on the cinefilm. Fig. 11. However, with 15° rotation, only the 2 mm. spaces could be clearly seen.

In all the cases investigated, the head rotation has been less than 6° , as measured by the distance between the angles of the mandible.

In the assessment of whether or not closure between the posterior pharyngeal wall and the soft palate is complete, tilting of the head to one side or another is of minor importance. Such tilting must be at least 10 – 15° in extent to make assessment difficult. This has not been the case in our series.

For a more exact assessment of the interrelationship of the anatomical structures a moderate tilting of the head might be of importance. Fig. 13 shows that an apparent displacement of e.g. the highest point of closure between the soft palate and the posterior pharyngeal wall is 1 mm. when the head is tilted about 9° .

No tilting of the head exceeded 9° in our series. Since the error of the method of measurements in this region is more than 1 mm., a moderate tilting of the head is of no significance.

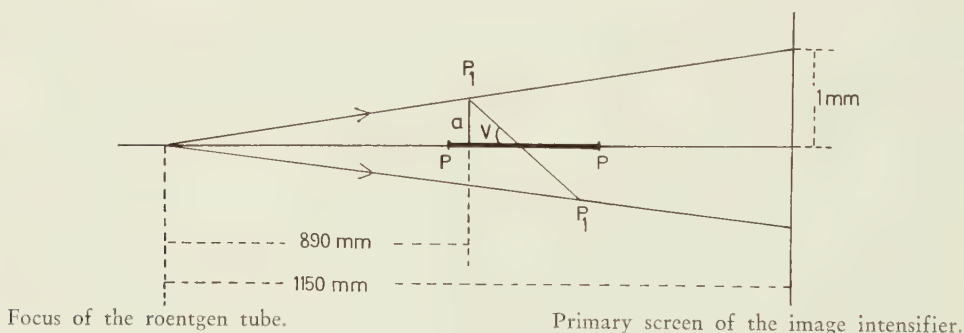


Fig. 13. PP in a horizontal line on the posterior surface of the soft palate.

$P_1 P_2$ is the same line when the head is tilted v° . The projection of the point P is then displaced 1 mm. If the line PP is 100 mm. and the other distances as in the Figure: $a = \frac{890}{1150}$ mm.; $\tan v = \frac{890}{1150 \times 5}$; $v = 9^\circ$.

3. Variations in the minimum distance between the soft palate and the posterior pharyngeal wall during opening and closure of the velopharynx

The earlier mentioned diagrams of the movements of the soft palate during the reading of the test sentences are based on observations of all the movements of the soft palate. However the soft palate may move upwards or downwards without any change in the minimum distance between the soft palate and the posterior pharyngeal wall. The minimum distance may be said to represent the size of the coupling area between the nasal and oral cavities, (see Chap. III, p. 41). It was therefore considered important to measure the variations in this distance during opening and closure.

Material

Six experimental subjects were used for this investigation, 3 men and 3 women. Every subject read the test sentences at normal speed, as fast as possible and as slowly as possible without making a pause between words or syllables. Fifty-four test sentences in these six subjects were used.

Method

The films from these 54 test sentences were projected on to the screen of the viewer and the minimum distance between the posterior pharyngeal wall and the soft palate measured. This distance was measured with every frame. The distance between the posterior pharyngeal wall and the soft palate in the "resting position" was also measured. In the diagrams (Fig. 14) the distance on each frame between the soft palate and the posterior pharyngeal wall is given as % of the maximum opening in the "resting position".

Results

The results are shown in Fig. 14. In these diagrams have also been drawn the curves representing the total movement of the soft palate. It is seen that both curves agree rather well. The shapes of the curves are strikingly similar with few exceptions. Deviations between the two curves amount to usually not more than 10 % of the total opening for single frames and exceptionally reaching 15 %

Comparison of these two curves thus show that measurement between the posterior pharyngeal wall and the soft palate can be obtained with an error of up to about 10 % from the curves of the soft palate's total movements. The two measurements which must be taken are the distance between the soft palate and the posterior pharyngeal wall at the lowest point of the curve of total



Fig. 14. Variations in the minimal distance between the soft palate and the posterior pharyngeal wall during opening-closing movements in the test sentences used. 0 % indicates velopharyngeal closure and 100 % maximal opening. The dotted lines represent the total movements of the soft palate as used in the diagrams in Fig. 27, 29, 30, 31.

movement and the distance between the soft palate and posterior pharyngeal wall in the "resting position".

The above is for diagrams of an opening followed by a closure in the middle of the test sentences at the nasal consonant "n".

If the diagrams of the schematic total palate movement during the reading of the test word "mamma" in "Mammas fina schal" ("Mummy's fine shawl") are compared with the measured distance between the soft palate and the posterior pharyngeal wall, agreement is sometimes not as good. Thus with this test word the simple procedure mentioned above cannot be used. Instead it is necessary to measure the distance between the soft palate and the posterior

pharyngeal wall directly on each frame. This is probably the case also with the word "ingen" in the test sentence "Ingen var vaken vid midnatt" (No one was awake at midnight) since there were great individual variations in the movement pattern of the soft palate during pronunciation of this word.

4. The error of the method in the measurements of the soft palate and the pharyngeal wall

To determine the standard error of measuring the distance soft palate-pharyngeal wall directly on the viewing screen (p. 27), double measurements have been made completely independently of each other of 78 distances in 3 experimental subjects. The results are shown in the following table.

Difference (absolute value in mm.) between first and second determination	0	0.2	0.3	0.5	1.0
No. cases	37	4	3	33	1

Distances smaller than 1/2 mm. are difficult to estimate accurately. It is therefore also difficult to determine the error of the method S_m . An attempt to estimate S_m gives 0.25.

From the above it can be seen that the technique used by us of directly measuring the distance soft palate-posterior pharyngeal wall is a safe method. With our technique this method gives a more certain result than to make measurements secondarily from tracings. See Chap. IV, p. 47.

In our experience it is easier to make measurements directly on the projected picture than to make tracings and then measure them. Since the accuracy of our method with direct measurement is good, we have no reason to recommend making tracings first and then measuring them. With improved technique and better care in making the tracings we could probably achieve greater accuracy in measuring them. One advantage with tracings is that they can be used for measuring distances other than that originally intended at a later date. MOLL (1960) found greater accuracy by measuring tracings than by measuring directly on the projected picture. Why our result is the opposite is not clear but may depend on differences in technique and apparatus.

5. The error of the method in interval determinations

The accuracy of the method for determining the frame on which a particular palate movement begins or ends was investigated on a series of 209 double determinations made on five different roentgen cinefilms. The error of the method (S_m) expressed in the form standard deviation from a difference of 0 between the determinations is calculated according to the formula $S_m^2 = d^2/2$

$(n-1)$, when d is the observed difference between both determinations and n is the number of double determinations.

The 209 double determinations gave $S_m = 0.84$. From these figures it can be estimated that the error in a single determination is greater than two frames with a probability of 0.02.

Since measurement of the interval involves determination of the distance between two frames, the error of the method in this case is somewhat greater, i.e. $S_m = 1.08$. The probability is 0.06 that the error in a single interval measurement is more than two frames.

From the above it is seen that with a single determination, it may be assumed that there is an error in the determination of two frames. With the frame frequency used, this corresponds to 40 msec., and on the Sund spectrogram about 2 mm. Thus with single cases of synchronization between the diagram after palate movements and the Sund spectrogram, variations less than 40 msec. are of no significance.

CHAPTER III

Tomographic Investigations of the Velopharynx

In order to be able to assess the possibilities of studying velopharyngeal closure in normal subjects using cineradiography only in lateral projection, a more accurate knowledge of the anatomy of the velopharynx during active articulation has been necessary. It has not been possible to find details of this anatomy in the literature. The available details have referred only to dead subjects.

Furthermore it was important to find out more of the anatomical interrelationships and their variations during articulation in patients operated with a pharyngeal flap. (See Chap. III, p. 34.) In these patients a soft-tissue flap is inserted between the soft palate and the posterior pharyngeal wall in the mid-line. The aim of the investigations of these patients has been to determine the amount of information concerning the anatomy of the soft palate and the conditions for assessment of velopharyngeal closure which can be obtained using roentgen cinefilm in lateral projection.

In order to confirm the acoustic theories and calculations of nasality, it is of great importance to be able to establish the size of the opening which connects the nasopharynx with the lower part of the pharynx and oral cavity (FANT 1957, FUJIMURA 1960 etc.). No method has been developed for reproducing the cross-sectional area of this opening during continuous speech and thus following its variations. On the other hand, using transversal tomography, it seems possible with fairly good accuracy to reproduce this area during the production of single sustained sounds.

1. Rectilinear simultaneous tomography

Method

In order to solve the first two problems, Siemens Universal Planigraf has been used. This apparatus is a rectilinear tomograph. It is equipped for simultaneous tomography. Using this apparatus, seven tomographic sections of the velopharynx at a distance of 5 mm. from each other have been obtained with one roentgen exposure. The exposure data were 115 kV, 40 mA, exposure time 0.8 sec. The patient was sitting upright. Because of the construction of the apparatus, the direction of the tomographic movement of the roentgen tube

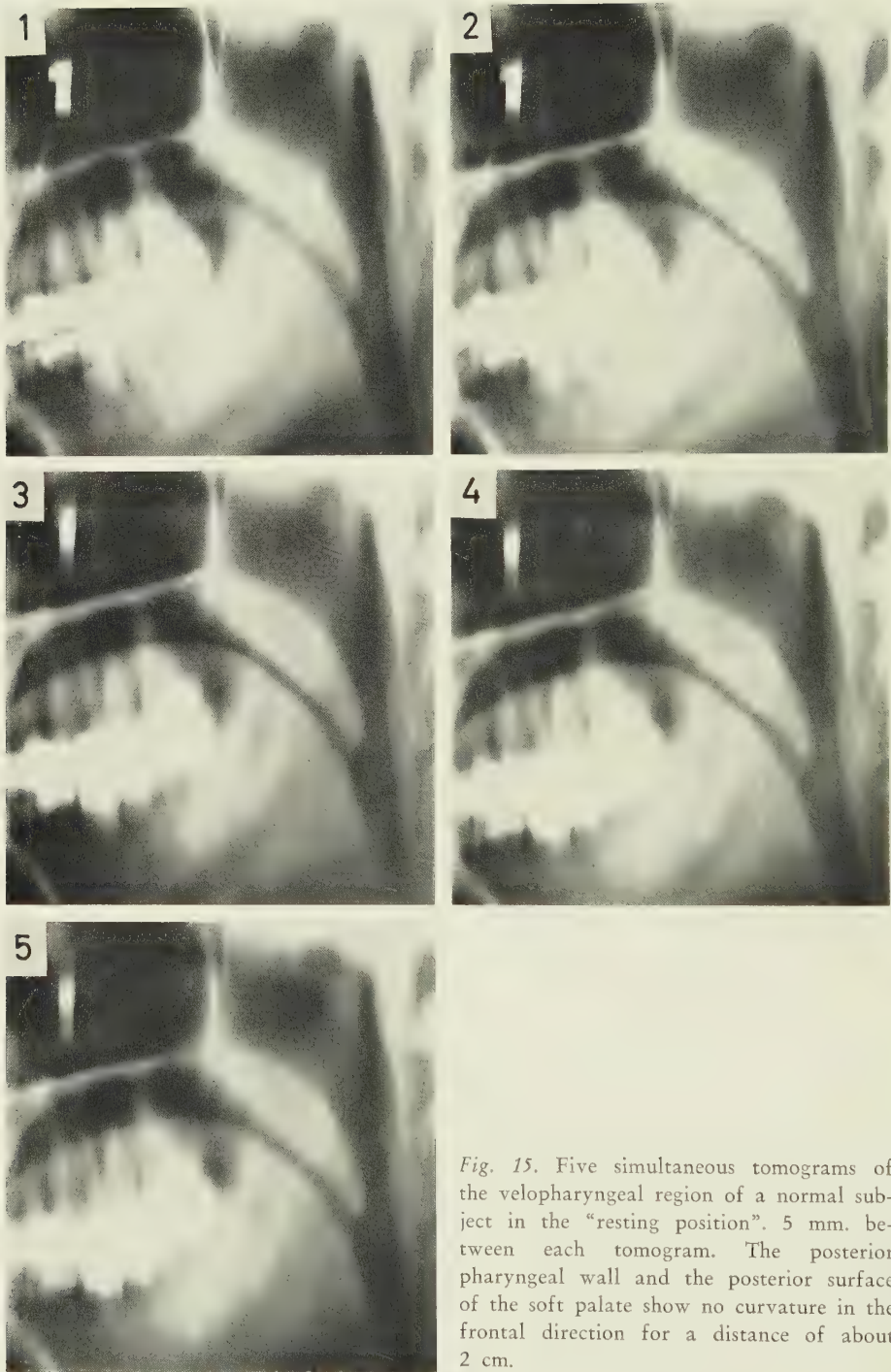


Fig. 15. Five simultaneous tomograms of the velopharyngeal region of a normal subject in the "resting position". 5 mm. between each tomogram. The posterior pharyngeal wall and the posterior surface of the soft palate show no curvature in the frontal direction for a distance of about 2 cm.

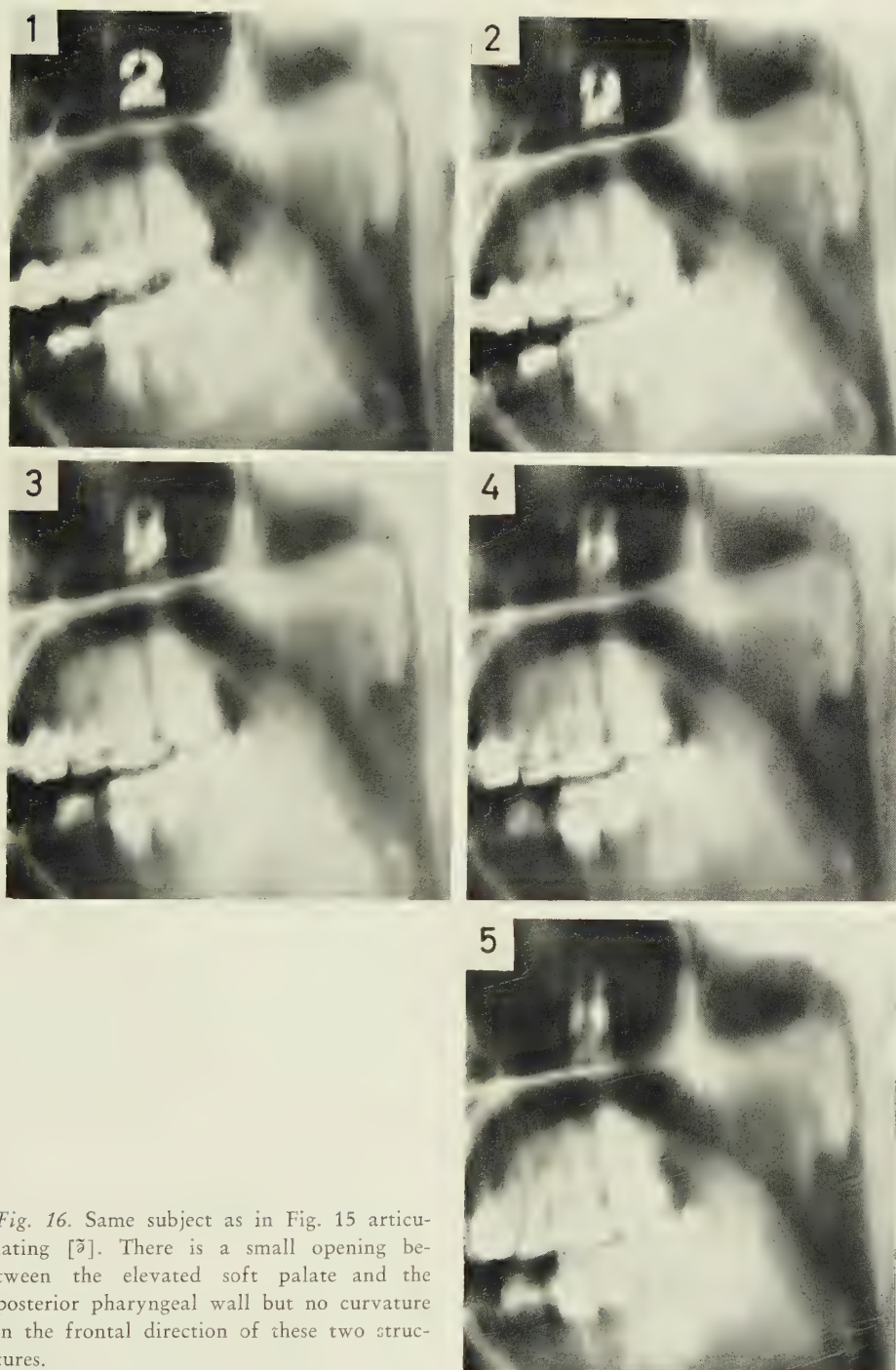


Fig. 16. Same subject as in Fig. 15 articulating [ʒ]. There is a small opening between the elevated soft palate and the posterior pharyngeal wall but no curvature in the frontal direction of these two structures.

and roentgen film coincide with the patient's long axis. Since the posterior pharyngeal wall and posterior surface of the soft palate in adults are vertical, it would be more suitable from the point of view of tomographic reproduction if the direction of movement were at right angles to the one used. However, because of the construction of the apparatus this has not been possible without having the patient lying down, which would change the position of the speech organ and thereby the quality of the sound produced. In addition, it was important to examine the patients and subjects in the same position as during cineradiography.

A. INVESTIGATIONS OF NORMAL SUBJECTS

Material

Examination was made of ten normal-speaking adults. Three exposures were made in each. During the first, instructions were given to breathe calmly through the nose during tomography. In this way, a picture was obtained with the speech organs in the resting position. In the next exposure, the patient was instructed to produce the sound [m]. In the third investigation the patients were told to produce the sound [ẽ] or [i].

Results

The following observations were made in all ten cases. In the resting position, the posterior pharyngeal wall is largely flat for a distance of c. 1 cm. on either side of the midline. Afterwards it deviates forwards, but exactly where cannot be determined. Fig. 15.

Similarly, the posterior surface of the soft palate in the resting position is seen to be flat for a distance of c. 1 cm. on either side of the midline. Fig. 15.

During articulation of the sounds [m] and [ẽ], no change in this state can be shown. Thus during articulation of these sounds the posterior surface of the palate is flat and parallel to the frontal plane for a distance of c. 2 cm. Similarly, the posterior pharyngeal wall is largely flat and parallel to the frontal plane for a corresponding distance. A deviation then follows of the posterior pharyngeal wall and the posterior surface of the soft palate on both sides relatively quickly. Exactly where this deviation occurs and how great it is cannot be determined by this method. Fig. 16.

B. INVESTIGATIONS OF OPERATED CLEFT PALATE PATIENTS

Material

Examination was made of nine patients operated with a pharyngeal flap and one operated by Hynes' method (See NYLÉN 1961, Chap. IV). On inspection, these patients showed large variations in length and mobility of the soft

palate. Furthermore, the openings on each side of the flap showed large variations. Similarly the patients' speech varied from normal to definitely nasal. The methods used were the same as these described above.

Results

In these tomographic investigations it was easy to see the pharyngeal flap, its dimensions and relationship to the soft palate. It was seen that the pharyngeal flap was usually in the midline and that the openings on each side were largely symmetrical. However in one case a significant asymmetry was seen. On the tomograms the soft palate was clearly distinguishable from the pharyngeal flap. (Fig. 17.) Any closure between the posterior pharyngeal wall and the soft palate and the flap has been clearly defined by this method. (Fig. 18.) There was good agreement between the simultaneous tomographic method and roentgen cinefilm in lateral projection in assessing velopharyngeal closure. In five cases velopharyngeal closure was confirmed by both cineradiography and tomography. In three cases, both methods confirmed velopharyngeal incompetence. Closure was judged to be incomplete with tomography in two cases. However cineradiography in these latter cases showed closure with certain sound combinations, although closure was incomplete in other combinations. In these two cases, cineradiography with its possibilities of recording several closing movements under connected speech, gives more reliable information of anatomy and function than simultaneous tomography.

It is apparent that roentgen cineradiography in lateral projection is a reliable method in cases operated by pharyngeal flap for assessing velopharyngeal closure.

The fact that in the majority of these cases, the pharyngeal flap was seen indistinctly or not at all can be explained by its small dimensions in the frontal plane compared with the soft palate. Because of this, the soft palate appears much more distinctly than the pharyngeal flap in a picture in which the structures are superimposed, such as a roentgen cinefilm in lateral projection. This means that if a closure between the soft palate and the posterior pharyngeal wall is seen, then closure is a fact and not an illusion caused by the pharyngeal flap.

2. Transversal tomography of the velopharynx

As mentioned above, it is of great importance for the acoustic assessment of normal and pathological nasality that the minimal cross-sectional area of the passage between the nasal and oral cavities is known. If such a passage exists in normal subjects, it is in the form of a tube somewhere between the soft palate



Fig. 17. Five simultaneous tomograms of the velopharyngeal region of a cleft palate patient operated with a pharyngeal flap. "Resting position". 5 mm. between each tomogram. The flap in the midline between the soft palate and the pharyngeal wall is well defined only in tomogram 3. In the other tomograms the openings on both sides of the flap are seen.

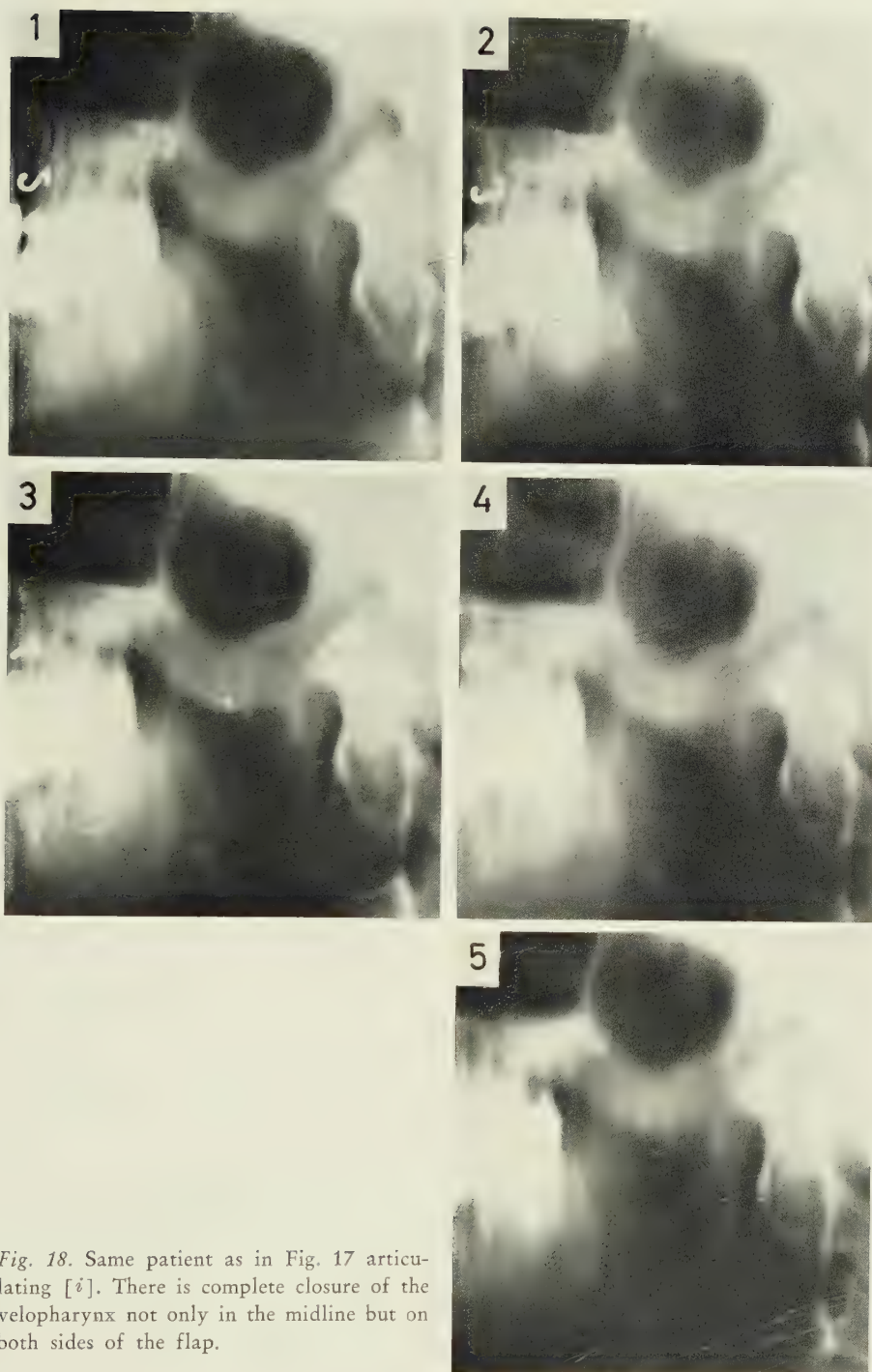


Fig. 18. Same patient as in Fig. 17 articulating [i]. There is complete closure of the velopharynx not only in the midline but on both sides of the flap.

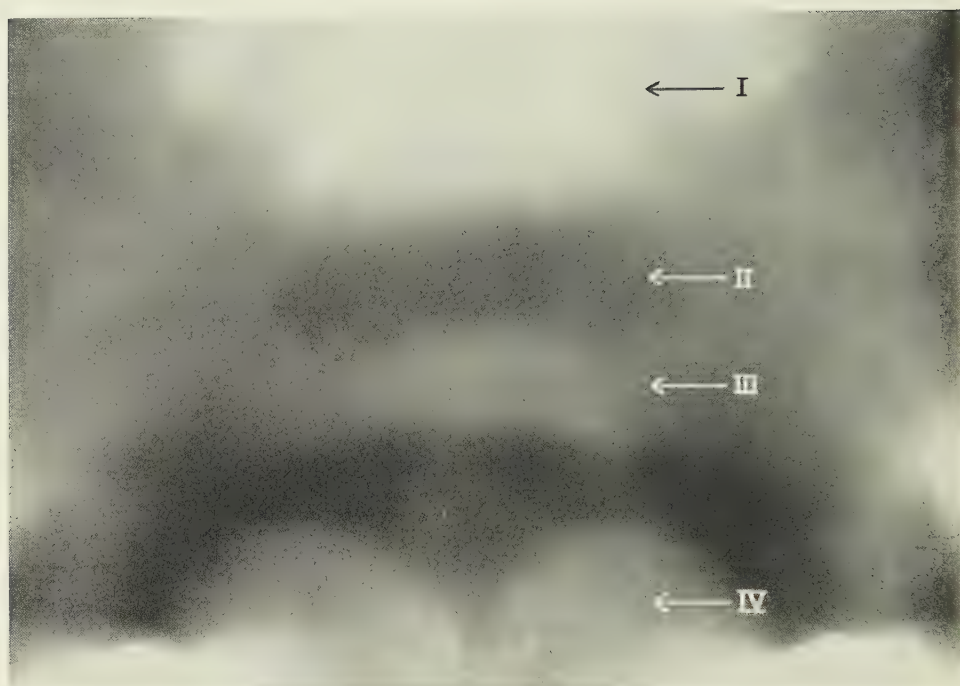


Fig. 19. Transversal tomogram of the velopharynx of a normal subject articulating [m]. I. Bony structure of the atlas and the axis. II. Cross-section of the coupling gate between oral and nasal cavities. III. The soft palate. IV. The base of the tongue with depression in the midline.

and the posterior pharyngeal wall. There is no information on shape, size and variations in cross-sectional area of this tube with different sounds. The assessments that have been made of this area, are based on rough approximations. We have not been able to find any method for investigating the variations in this area during connected speech. On the other hand, during production of sustained sound, this area can be reproduced with rather good accuracy using transversal tomography.

Method

The apparatus used was a Pantix Strator transversal tomograph. In this apparatus, the roentgen tube was fixed, patient and roentgen film rotating horizontally. The patient sat upright on a special chair, the roentgen film being exposed during 360° rotation. The exposure time was varied by changing the speed of rotation. With this method horizontal tomograms can be obtained at right angles to the long axis of the subject. Exposure data were 2.5 sec.,



Fig. 20. The same subject as in Fig. 19 articulating $[\tilde{e}]$. The area of the cross-section (II) has diminished considerably.

250 mA, 75–80 kV. The sound produced was in some cases recorded by a Sennheisser MD3 microphone and Lyrec tape recorder. For further details of transversal tomography, reference should first be made to GRIESBACH & KEMPER (1955) and GEBAUER & SCHANEN (1955).

Material

The method was tested on ten normally-speaking adults. They were examined while articulating $[m]$, $[\tilde{e}]$, $[\hat{i}]$ and in the resting position.

Results

1) In these investigations as in those described above with rectilinear tomography, it has been seen that the soft palate and posterior pharyngeal wall are largely parallel with each other and with the frontal plane for a distance of about 2 cm. The posterior pharyngeal wall then deviates forwards, though to

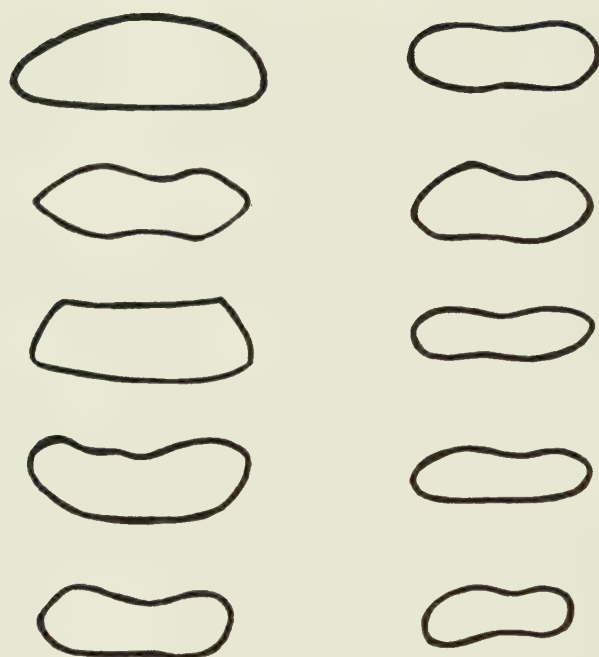


Fig. 21. Actual size in "resting position" of the cross-sectional area of the coupling gate between oral and nasal cavities. The cross-sections are traced from transversal tomograms of the velopharynx in ten normal speaking adults.

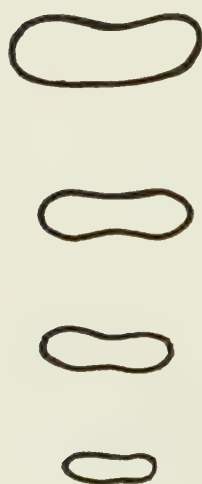


Fig. 22. Variations in size and shape of the cross-section of the coupling gate between oral and nasal cavities in one experimental subject. Tracings from transversal tomograms in (from above) "resting position", and articulating $[m]$, $[\tilde{\eta}]$ and $[\tilde{\epsilon}]$.

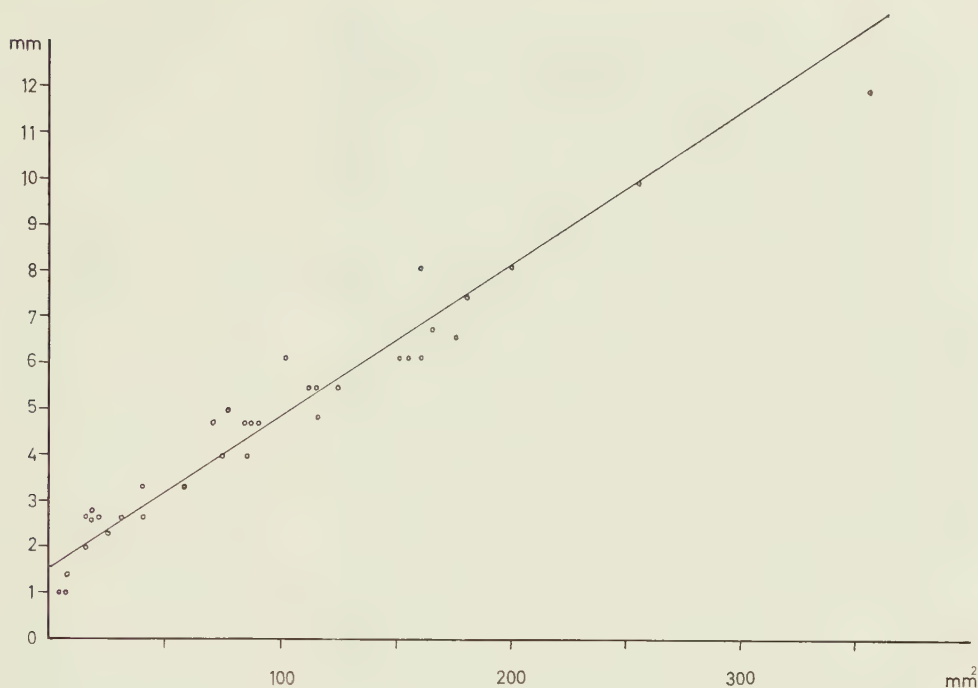


Fig. 23. Diagram showing the sagittal minor axis (mm.) of the cross-section of the coupling gate between nasal and oral cavities in relation to the area of the cross-section (mm².) in 10 normal test subjects.

a less extent than the soft palate which deviates backwards more acutely. Thus the cross-section of the space between the soft palate and the posterior pharyngeal wall has the shape of a somewhat asymmetrical ellipse with its major axis horizontally in the frontal plane. (Fig. 19 and 20.) The variations in the appearance of the cross-section in various experimental subjects is shown in Fig. 21.

2) During intonation of various nasalized sounds the size of the cross-section varies, as e.g. in Fig. 22. The area diminishes with increasing velopharyngeal closure in both frontal and sagittal planes.

If the area of the cross-section in mm² is plotted along the x-axis and the sagittal minor axis in mm. along the y-axis on a graph, the result obtained for all the determinations in the ten experimental subjects is as shown in Fig. 23.

It can be seen that there is a linear relationship between the sagittal minor axis of the cross-section and its area.

This means that the cross-section, i.e. the size of the coupling area between the nasal and oral cavities can be determined using only the measure of the minor axis.

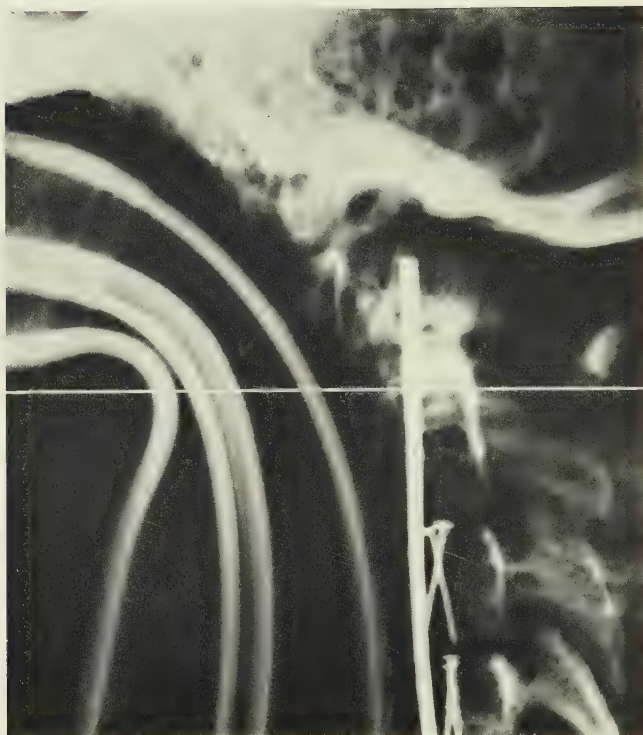


Fig. 24. Experimental model to study possible deformation of the velopharyngeal region during transversal tomographic reproduction. Two plastic tubes bent at right angles represent the base of the tongue, the soft palate and the posterior pharyngeal wall and the air passages between these structures. The tubes are placed under a dry skull with its upper cervical vertebrae. 6 cm. of plexiglass are added. A transversal tomogram (Fig. 25) is taken approximately at the line marked in the figure.

This measure is easily obtained from a lateral view of the speech organs, e.g. the cineradiographic films used by us.

The size of the coupling area thus obtained can then be exactly correlated with the corresponding section of the spectrogram by using our synchronization device. In this way, the variations in the size of the coupling area and their effect on the spectrogram can be studied.

To find out if the cross section of the space between the soft palate and the posterior pharyngeal wall is distorted during tomographic reproduction, a model experiment was performed. The pharynx was simulated by two plastic tubes bent at a right angle and placed at the site of the pharynx under a dry skull with its corresponding upper cervical vertebrae. Six cm. of plexiglass was added to simulate soft tissues. Fig. 24.

Transversal tomograms were taken of this model at a height corresponding to the soft palate and it was seen that the lumen of the plastic tubes was not distorted during tomographic reproduction. Fig. 25.

This result is for normal adults. In these connection between the nasal and oral cavities is shaped like a tube extending one or two cm. vertically.



Fig. 25. Transversal tomogram of the model seen in Fig. 24. The cross-section of the tube $\leftarrow$ representing the coupling gate between nasal and oral cavities is not deformed at the tomographic reproduction.

The cross-sectional area of this tube would be relatively unchanged for a distance of 1/2–1 cm. This facilitates the tomographic reproduction.

The variations of this cross-section in operated cleft palate cases with their frequently changed anatomy are great from one case to the next. This is especially so in cases with a pharyngeal flap. Because of this, the results obtained in normal adults cannot be considered valid for cleft palate patients.

However, the graph (Fig. 23) of the relationship between the cross-sectional area and sagittal axis can be used for an approximate determination of the size of the coupling area between the nasal and oral cavities in patients operated for cleft palate.

CHAPTER IV

Cineradiographic and Sound Spectrographic Studies in Normal Experimental Subjects

1. Material

The material consisted of 17 adult men, 14 adult women and 26 children five to eight years of age.

All of the experimental subjects included in the material have been considered "normal speaking" by us and their normal acquaintances, i.e. there have been no obvious speech disturbances. In children, assessment has obviously been influenced by considerations of age and speech development.

In the series of men, thirteen were doctors or medical students. The remaining four were patients under treatment in the hospital for peripheral injuries. In the series of women thirteen were female personnel in the roentgen department. One was a housewife. In the series of children, fourteen were children of doctors. The remaining twelve were patients under treatment in hospital for conditions considered by us as having no effect on the function of the speech organs.

A listening test, (see p. 45) was carried out and a moderate nasality was found in four children and one adult. The others were considered as having no or very insignificant nasality.

Complete test (filming for up to 20 sec. and reading of four or five test sentences) was performed in 13 men, 14 women and 21 children.

Supplementary test (test sentence: "Ingen var vaken vid midnatt".—No one was awake at midnight) was performed in four men.

Slow-reading test was performed in three men and three women.

Fast-reading test was performed in three men and three women.

Special test to study the nasalization of certain vowels was performed in three men.

Special test with normal subjects simulating the nasal speech of cleft palate cases was performed in four men.

2. Results of listening test

All the normal experimental subjects underwent the listening test described by NYLÉN (1961) Chap. IX. They were assessed using the same principles as the operated cleft palate cases undergoing the test.

ADULTS

The majority of the 31 experimental subjects were assessed as having no nasality.

One experimental subject was assessed as having a moderate or slight nasality. Four experimental subjects were at least once assessed as having slight nasality. (Tab. 1.)

As seen in the table, female experimental subject no. 11 was assessed throughout as having a moderate or slight nasality by both listeners. The other results in the table show a less satisfactory agreement between the various occasions on which the patients were assessed. Since the speech of the four experimental subjects on a majority of occasions was assessed as being non-nasal, their speech could be taken as normal. One listener W. was stricter in his assessment than listener L., but there was some variability in assessment in both listeners.

Table 1
Nasality. Adults.

Experimental subject	Listener W	Listener L
11 ♀	Slight	Moderate
„	Slight	Moderate
„	Slight	Slight
„	Slight	Slight
„	Slight	Slight
2 ♀	Slight	None
„	None	None
„	None	None
„	None	None
„	None	None
6 ♀	Slight	None
„	Slight	None
„	Slight	None
„	None	None
3 ♂	Slight	Slight
„	Slight	None
„	None	None
„	None	None
8 ♂	Slight	None
„	None	None
„	None	None
„	None	None

Table 2
Nasality. Children.

Experimental subject	Listener W	Listener L
3	Moderate	None
12	Moderate	Moderate
12	Slight	None
25	Moderate	Slight
25	Slight	Slight
26	Moderate	Slight
2	Slight	None
4	Slight	None
4	None	Slight
5	None	Slight
5	Slight	Slight
9	Slight	None
9	Slight	Slight
10	None	Slight
11	Slight	None
13	Slight	None
15	Slight	None
16	Slight	None
18	None	Slight
20	Slight	None
24	None	Slight

The female experimental subject no. 11 who was consistently assessed as having a moderate or slight nasality showed no obvious deviation in her diagram of palatal movements from those of the other experimental subjects. There was no obvious difference found between this experimental subject and the others either with regard to correlation between palatal movements and respective sounds as seen on the spectrogram. Finally, there was no obvious difference on the Sund spectrogram between this experimental subject and the others. The same is true of the other experimental subjects mentioned in Table 1, who at least once were assessed as having a slight nasality.

CHILDREN

Four of the 26 children have on some occasion been assessed as having moderate nasality. 12 of the children have on some occasion been assessed as having slight nasality. The results of the various assessments in these experimental subjects appears in Table 2.

Two of the children who on some occasion were assessed as having a moderate nasality, read the test sentences completely and it was possible to synchronize the spectrograms with the palatal movements. No definite deviations in the palate movements or relationship between palate movements and sound produced could be shown in these two cases. Of the other two cases with moderate nasality, one spoke only isolated words and with the other no synchronizing was possible because of a technical fault during the recording.

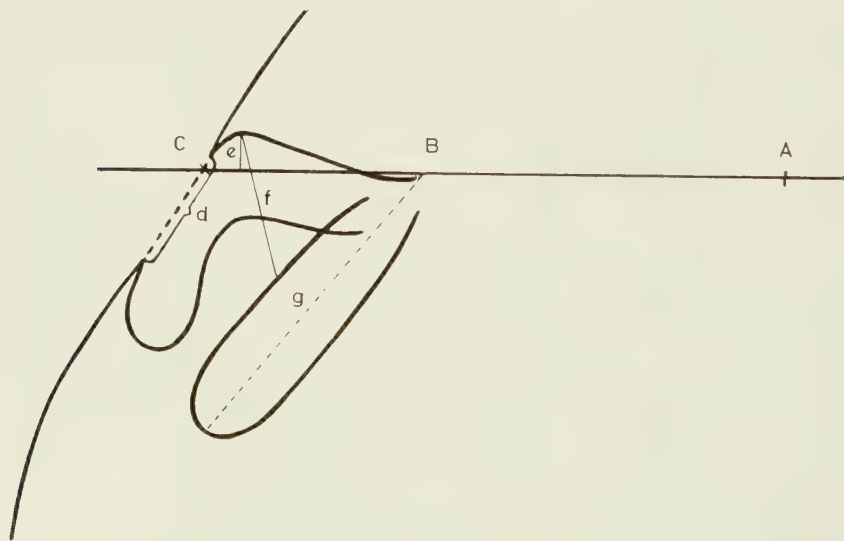


Fig. 26. Diagram showing distances measured from tracings of the soft palate and nearby structures.

With the 12 experimental subjects who some time were assessed as having a mild nasality, the variations between both listeners and even between their assessments of a particular subject from one time to another were considerable.

That as many as 16 experimental subjects in a group of 26 were judged as having a definite nasality, need not only be attributed to inconsistency in the listeners, but can also reflect the difficulties in deciding what is normal for children of this age. This result of the listening test implies that a certain nasality is a normal part of speech in about one half of children in this age group.

3. Measurements of the soft palate and neighbouring structures

Measurements were made on tracings of typical positions of the soft palate in 17 men, 14 women and 25 children.

These measurements are given in Fig. 26.

AB = the distance from the anterior nasal spine to the posterior border of the hard palate.

BC = the distance from the posterior border of the hard palate to the posterior pharyngeal wall along a line coinciding with the plane of the hard palate.

d = the length of the surface of the soft palate in contact with the posterior pharyngeal wall during velopharyngeal closure.

e = the distance from the highest point of the soft palate to the line AC. e is positive if the point is above the line AC and negative if below the line AC.

f = a measure of the total movement of the soft palate. It is obtained by projecting the distance from B to the highest point of the soft palate down to the posterior border of the soft palate in the resting position. The distance between the point thus obtained and highest point of the soft palate is the distance f. This distance is considered to give some estimate of the total movement of the soft palate during closure. Because of the change in shape of the soft palate during closure there is no guarantee that the two limits of the distance f correspond to exactly the same point on the soft palate. However, in our opinion, the distance f gives a better idea of the possibilities of movement of the soft palate in two directions than only the minimum distance between the posterior border of the soft palate and the posterior pharyngeal wall in the resting position.

g = the total length of the soft palate including the uvula, measured from the posterior border of the hard palate (B) to the top of the uvula in the resting position.

The results of these measurements are shown in Table 3, where the mean value $\pm$ standard error is given in mm.

Table 3*Distances measured from tracings of the soft palate and nearby structures.*

Distance	Adults			Children, both sexes
	males	females	both sexes	
AB	—	—	—	32.0 ± 0.6
BC	24.9 ± 1.1	25.1 ± 0.7	25.0 ± 0.7	17.0 ± 1.0
d	13.1 ± 0.4	12.9 ± 0.8	13.0 ± 0.4	9.3 ± 0.3
e	$+ 6.0 \pm 0.9$	$+ 5.9 \pm 0.8$	$+ 5.9 \pm 0.6$	$+ 0.7 \pm 0.5$
f	21.8 ± 1.1	21.2 ± 1.0	21.5 ± 0.8	10.4 ± 0.7
g	28.8 ± 0.5	27.6 ± 0.7	28.3 ± 0.4	23.0 ± 0.5

It has only been possible to measure AB in a few of the adult experimental subjects, so that it was not possible to calculate a mean.

The table shows that there is no great difference between men and women in this series.

As expected, the measurements are generally less in children than in adults. However it is striking how large relatively the length (g) of the soft palate is in children. In addition, it is seen that the upper point of closure of the soft palate against the posterior pharyngeal wall in children lies lower than in adults. This is associated with the more forward-sloping posterior pharyngeal wall in children compared with the almost vertical posterior pharyngeal wall in adults.

A calculation of the error of the method of these measurements was carried out on 35 observations of the same distance on two different roentgen films and a value of $S_m = 1.8$ was obtained. From this it may be calculated that the error in a single determination with a probability 0.9 is at the most 3 mm. and with a probability 0.2 exceeds 4 mm.

Thus the error of the method in our technique of measuring these distances via tracings is considerable. In a similar investigation of measurements of soft tissue structures, MOLL (1960) found a similar error of the method.

The aim of these measurements in normal subjects has not been to make exact measurements in the velopharyngeal area. The measurements were made mainly as a basis for assessment of the corresponding distance using the same technique in operated cleft palate cases.

4. Studies of movements of the soft palate during connected speech

In these studies 16 adult men, 14 adult women and 21 children were used as experimental subjects. The following test sentences were used.

- 1) Mammas fina schal
Mummy's fine shawl

- 2) Polisen tog boven i badet
The policeman caught the villain in the bath
- 3) Gatan var hal av is
The street was slippery with ice
- 4) Ingen var vaken vid midnatt
No one was awake at midnight

Results

- 1) *Mammas fina schal*, ~*mammas* ~*fi:na* fa:l, (Mummy's fine shawl)

The movements of the soft palate in normally-speaking subjects are largely similar to these in the diagram drawn in Fig. 27. In this diagram time is represented from left to right along the x-axis. The percentage closure between soft palate and posterior pharyngeal wall is marked on the y-axis. Thus 100 % implies complete closure and 0 % maximal opening. This diagram was obtained by following all the movements of the soft palate, frame by frame on the roentgen cinefilm. The various phases of the movements or positions of the soft palate have been numbered 1-8.

With the sentence "Mammas fina schal", the test was carried out correctly in 12 men, 14 women and 14 children. The other experimental subjects (7 children and 1 man) carried out the test incorrectly because the instructions were inadequately followed for the time of commencing speech, correct pronunciation of the test sentences, pauses between the test sentences, etc.

The pattern of movement shown in Fig. 27 was completely followed by 8 of the 12 men, 5 of the 14 women and 12 of the 14 children. All the other experimental subjects followed the pattern of movement, at least with interval No. 1 and intervals 4-8.

Variations were seen in intervals 2 and 3. In 15 cases they consisted of an extra downward movement of the soft palate, followed by a stationary partial closing position, lower than the one corresponding to the ordinary interval 2 before the definitive closing movement corresponding to interval 3 in the diagram. A few examples of variations in this series of movements is seen in Fig. 28. In two cases the palate showed no distinct plateau corresponding to interval 2, intervals 2 and 3 uniting to form a uniformly rising curve.

For statistical calculation in the cases where the movement pattern deviates from the standard, the following approximation was made. Interval 3 was called the closing movement which leads to definite closure. Interval 2 was called the distance between intervals 1 and 3 independently of whether this was a horizontal line as in the prototype curve or several movements. In the two cases when no division could be found between intervals 2 and 3, half of this distance was calculated as interval 2 and half as interval 3. Using these approximations, a table has been made of the mean percentage distribution be-

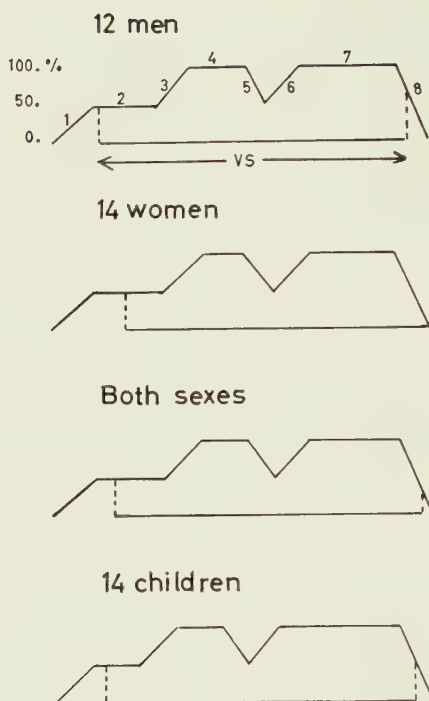


Fig. 27. Diagram of palatal movements during test sentence "Mammas fina schal", ~*mammas* ~*fi.na fa:l* (Mummy's fine shawl). 100 % indicates complete velopharyngeal closure and 0 % maximum opening between soft palate and posterior pharyngeal wall. VS: length of voiced sound as seen on the Sund spectrogram.

tween the intervals. (Table 4.) A diagram of the palatal movements derived from this table is shown in Fig. 27.

The table and diagram show that the percentage distribution by intervals differs between men and women, interval 4 being longer in men than in women and interval 5 being shorter in men than in women. The reason for this difference is not clear but may have something to do with different way of pronouncing "Mammas" and a greater tendency for women to nasalize the i-sound in "fina".

The difference between adults and children is in interval 2 which is shorter in children and in interval 7 which is longer in children than in adults. The reason for this is that children usually pronounce "Mammas" faster than adults. This is a word which they are familiar with and used to saying. The reason why interval 7 is longer in children may be that children are somewhat more tense during the test than adults. They therefore keep the palate closed longer after

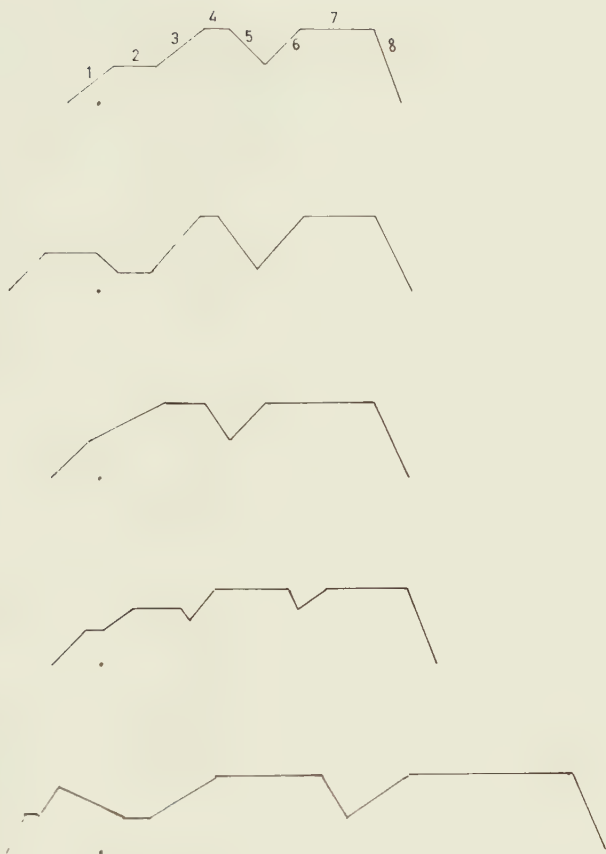


Fig. 28. Individual variations in the pattern of movements of the soft palate during the test sentence "Mammās finā šal" *˜māmmās ˜fi:nā šā:l* (Mummy's fine shawl). The point indicates the beginning of voiced sound.

Table 4
Test sentence "Mammās finā šal".

Interval no	Movement or position of the soft palate	Mean percentage distribution by intervals			
		Adults			14 children both sexes
		12 men	14 women	both sexes	
1	closure	11.0	11.7	11.4	10.4
2	half closed	17.3	18.6	18.0	12.3
3	closure	8.3	11.0	9.8	9.7
4	closed	14.9	9.9	12.2	12.0
5	opening	5.6	8.4	7.1	6.9
6	closure	8.9	9.6	9.3	8.4
7	closed	25.3	21.9	23.4	31.7
8	opening	8.7	8.9	8.8	8.6
Total		100.0	100.0	100.0	100.0
Silent interval		12.3	19.1	16.0	13.5
Voiced sound		81.6	81.4	81.5	81.5

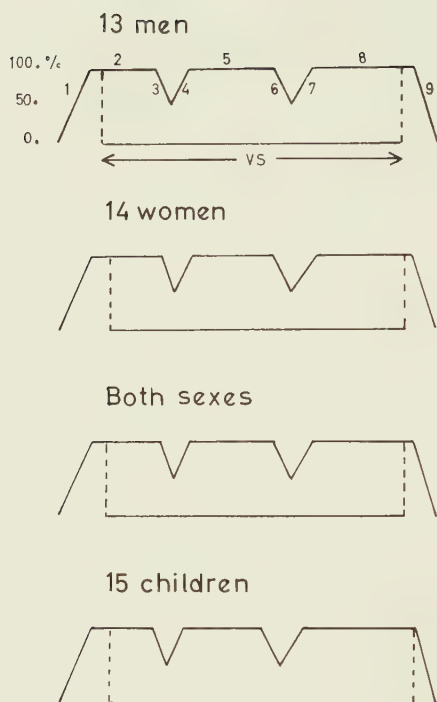


Fig. 29. Diagram of palatal movements during the test sentence "Polisen tog boven i badet", *pu'li:sən tu:g 'bu:vən i 'bɑ:dət*, (The policeman caught the villain in the bath).

the end of speech. The prolongation of this interval need not thus involve any definite difference between adults and children.

In the calculations of the means, the various intervals have been expressed as percent of the whole time taken by the individual experimental subjects to say the test sentences. These times have varied considerably, as also the time during which sound can be read on the spectrogram.

2) *Polisen tog boven i badet, pu'li:sən tu:g 'bu:vən i 'bɑ:dət*, (The policeman caught the villain in the bath)

The diagram of the movements of the soft palate while saying this test sentence drawn in the same way as for the sentence "Mammas fina schal" (Mummy's fine shawl) is shown in Fig. 29. The various intervals corresponding to the movements or position of the soft palate have been numbered from 1–9.

13 men, 14 women and 21 children were tested. A correct test was obtained

Table 5
Test sentence "Polisen tog boven i badet".

Interval no	Movement or position of the soft palate	Mean percentage distribution by intervals			
		A d u l t s			15 children both sexes
		13 men	14 women	both sexes	
1	closure	8.2	8.6	8.4	8.3
2	closed	17.3	18.3	17.8	16.7
3	opening	4.3	3.9	4.1	3.5
4	closure	4.6	4.4	4.5	4.3
5	closed	22.5	21.6	22.0	20.4
6	opening	4.3	5.0	4.7	5.7
7	closure	5.8	6.6	6.2	5.8
8	closed	26.9	25.3	26.1	29.6
9	opening	6.1	6.3	6.2	5.7
Total		100.0	100.0	100.0	100.0
Silent interval		11.2	13.6	12.4	13.5
Voiced sound		79.4	78.2	78.8	80.5

in 15 of the children. The other six did not completely obey the instructions given on pronunciation and pauses between the various sentences etc.

With the exception of one case all the men followed the pattern of movements of the soft palate. In this case, there was a short pause between "tog" and "boven" and during this pause the velopharynx partly opened. This pause was subtracted.

All the women followed the pattern of movements. Among the 15 children there were minor deviations in two, consisting of short pauses during the reading. However these pauses were subtracted. Following this movements correspond with the prototype.

The mean percentage distribution by intervals is shown in Table 5. A diagram of the movements of the soft palate derived from this table is shown in Fig. 29. These show that there is no significant difference between the movement pattern of men and women or of adults and children.

3) *Gatan var hal av is*, *˘gatan va ha:l av i:s*, (The street was slippery with ice)

A diagram of soft palate movements while this test sentence was being said is shown in Fig. 30. The various intervals corresponding to the movements or position of the palate have been numbered from 1-6.

This test was carried out in 13 men, 14 women and 21 children. The tests were correctly carried out in 13 men, 14 women and 18 children. With three

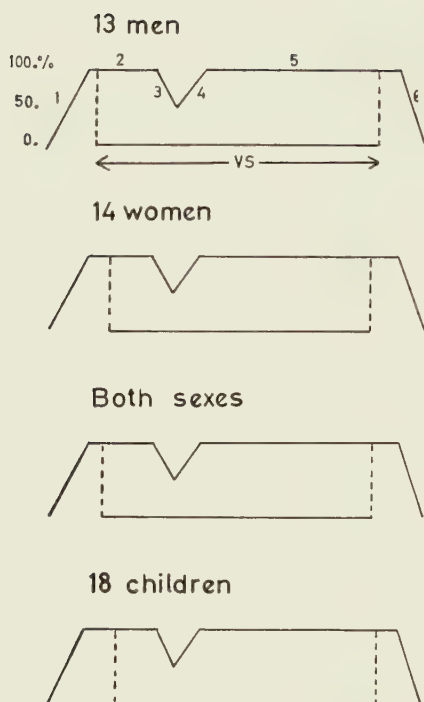


Fig. 30. Diagram of the movements of the soft palate during the test sentence "Gatan var hal av is", *ˈgɑ:tɑn vɑ hɑ:l ɑ:v i:s*, (The street was slippery with ice).

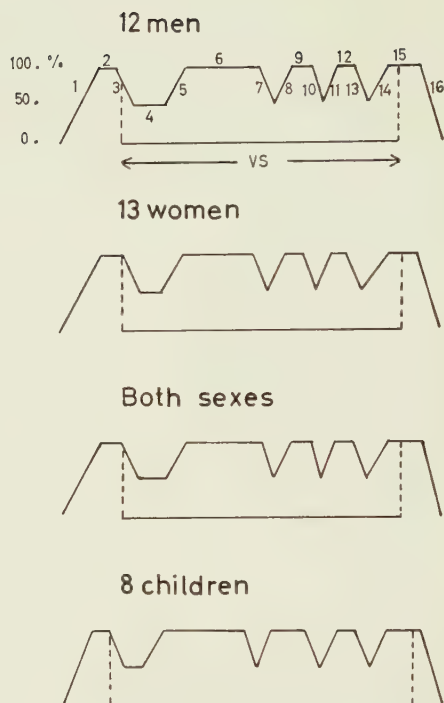


Fig. 31. Diagram of the movements of the soft palate during the test sentence "Ingen var vaken vid midnatt", *ˈiŋɡən vɑ ˈvɑ:kən vi:d ˈmi:dnɑt*, (No one was awake at midnight).

of the children the test was incorrect because they did not obey instructions about a pause between test sentences when reading. The only deviation from the soft palate movement diagram was in one adult male experimental subject. He spoke very slowly and the opening movement corresponding to interval 3-4 had a basal plateau in seven frames. He also made a pause between "var" and "hal" during which the velopharynx opens.

The mean percentage distribution by intervals is shown in Table 6 and diagram Fig. 30.

The table and diagram show that there is no significant difference between men and women or between adults and children in the movement pattern while speaking the test sentences.

Table 6
Test sentence "Gatan var hal av is".

Interval no	Movement or position of the soft palate	Mean percentage distribution by intervals			
		A d u l t s			18 children both sexes
		13 men	14 women	both sexes	
1	closure	10.3	10.6	10.4	9.6
2	closed	17.9	16.3	17.1	19.3
3	opening	5.8	5.9	5.9	4.5
4	closure	7.0	6.8	6.9	6.6
5	closed	52.7	53.0	52.8	53.0
6	opening	6.3	7.4	6.9	7.0
Total		100.0	100.0	100.0	100.0
Silent interval		12.3	16.0	14.2	17.9
Voiced sound		75.3	69.4	72.2	69.5

Variations in the length of speech and length of voiced sound are, as in the other test sentences, considerable.

4) *Ingen var vaken vid midnatt*, ˘iŋŋən va ˘va:kən vi:d ˘mi:dnat, (No one was awake at midnight)

The diagram of the movements of the soft palate while this test sentence is said are shown in Fig. 31. The various movements and positions of the palate are numbered from 1–16.

This test sentence was read by 14 men, 14 women and 12 children. In two men the test was incomplete for technical reasons (the film finished earlier than estimated). All 14 women completed the test. In two of the children the test was incomplete for technical reasons (the film finished earlier than estimated). In two of the children, the test was incomplete because of failure to obey instructions about the pause between test sentences during reading.

In this series variations and minor deviations from the movement pattern were seen in the intervals 2–4 and 5. Otherwise the movements were normal. The height of interval 2 varied. In some cases interval 2 corresponds to a complete closure, in other cases the palate is in an incomplete closure position corresponding to interval 2.

In five of the men the pattern described was followed exactly, even for intervals 2–5. In the other seven men, the pattern was followed except for interval 2, where closure was not complete, a small space being present between soft palate and posterior pharyngeal wall. The pattern was completely



Fig. 32. Individual variations in the pattern of movements of the soft palate during the test sentence "Ingen var vaken vid midnatt".

followed in three women. In ten the pattern was followed except that interval 2, corresponding to a position which does not correspond to a complete closure position in the soft palate, so that a small space has remained between the soft palate and the posterior pharyngeal wall. In one case, interval 3 does not consist of a plateau but corresponds to a slowly rising movement of the soft palate. In one other case, there is no clear interval 4 and intervals 3 and 5 go directly into each other. In seven of the children with a complete test, the movement pattern was correct. In one case there was some deviation in that a swallowing movement was made between "vid" and "midnatt". If this swallowing movement be subtracted, the movement pattern even for this experimental subject is normal. Examples of variations in the movement diagrams are shown in Fig. 32.

Table 7
Test sentence "Ingen var vaken vid midnatt".

Interval no	Movement or position of the soft palate	Mean percentage distribution by intervals			
		A d u l t s			8 children both sexes
		12 men	13 women	both sexes	
1	closure	10.3	10.9	10.6	8.5
2	closed	4.7	5.0	4.8	4.0
3	opening	4.4	4.6	4.5	3.6
4	half closed	8.5	6.1	7.3	4.9
5	closure	5.1	6.1	5.6	5.7
6	closed	19.5	18.8	19.2	20.8
7	opening	4.1	3.4	3.7	3.7
8	closure	4.5	4.7	4.6	4.1
9	closed	5.1	4.6	4.9	8.3
10	opening	2.8	3.2	3.0	3.7
11	closure	3.6	4.3	3.9	4.9
12	closed	4.5	3.7	4.1	4.5
13	opening	4.0	4.3	4.1	4.0
14	closure	5.2	7.2	6.2	4.9
15	closed	8.2	7.3	7.8	8.4
16	opening	5.5	5.8	5.7	6.0
Total		100.0	100.0	100.0	100.0
Silent interval		15.8	16.0	15.9	12.5
Voiced sound		72.4	73.6	73.0	79.2

The results of calculations of the mean percentage distribution by intervals are shown in Table 7 and in diagram Fig. 31. These show that there is no difference in movement pattern between men and women. There is probably a difference between adults and children with regard to intervals 4 and 9. Interval 4 is longer in adults than in children while interval 9 is shorter in adults than in children. Since there are only eight experimental subjects from the children's group, this result should be regarded with caution. "Ingen" is a word which children know well and pronounce rapidly. This can explain a shorter interval 4 in children than in adults. The latter part of the test is difficult to pronounce, "vid" being pronounced more slowly than in adults with a possible short pause between "vid" and "midnatt". This should be able to explain why children have a longer interval 9 than adults.

To summarize, these diagrams of the percentage distribution of the mean of the various intervals show a good agreement between the various groups. This means that the movements of the soft palate during normal speech follow a constant pattern. Opening and closing movements occur where expected,

viz. with nasal consonants and neighbouring vowels. In the complex series of functions, the end product of which we call "normal speech" the movement pattern of the soft palate is constant without noteworthy exceptions. This means that the diagrams of the movements of the soft palate in normal people described in this chapter can form a basis for the assessment of movements of the soft palate in operated cases of cleft palate.

5. The speed of palatal movements

The speeds of opening and closing movements of the soft palate showed large variations. It was not possible to measure the distance travelled by the soft palate during its movements. Therefore the time required for such a movement was used to represent the real mean speed. The times required for an opening and a closing movement in the test sentences in this investigation are shown in Table 8, with mean values in msec. for the various opening and closing times and maximum and minimum values for the movements in the different groups.

Table 8
Time required (msec.) for different palatal movements.
Test sentence "Mammās finā schal".

Interval number	12 Men			14 Women			14 Children		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
1. closure	60	243	340	80	247	320	40	210	540
3. closure	120	178	386	160	229	380	100	178	260
5. opening	40	117	220	100	174	280	80	127	180
6. closure	100	193	320	140	200	260	80	152	300
8. opening	120	185	420	100	183	300	100	155	240

Test sentence "Polisen tog boven i badet"

Interval number	13 Men			14 Women			15 Children		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
1. closure	160	234	580	180	233	320	100	201	360
3. opening	60	118	200	60	106	160	60	88	160
4. closure	60	128	200	80	119	160	80	108	170
6. opening	80	115	220	80	136	240	80	143	340
7. closure	80	168	300	120	180	380	60	148	340
9. opening	120	163	200	100	170	280	100	139	280

Test sentence "Gatan var hal av is".

Interval number	13 Men			14 Women			18 Children		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
1. closure	140	263	440	140	247	540	80	211	380
3. opening	80	144	230	80	139	200	40	99	220
4. closure	120	176	340	120	157	260	80	142	300
6. opening	80	149	200	100	171	220	60	155	320

Test sentence "Ingen var vaken vid midnatt".

Interval number	12 Men			13 Women			8 Children		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
1. closure	160	283	540	120	305	520	180	243	500
3. opening	80	123	180	40	122	260	80	101	160
5. closure	80	144	220	100	167	240	100	163	320
7. opening	40	118	200	40	94	140	40	108	200
8. closure	60	128	200	80	128	180	60	120	200
10. opening	40	75	140	40	89	160	60	108	200
11. closure	60	102	180	80	117	200	100	138	160
13. opening	60	113	240	60	115	180	60	113	180
14. closure	100	142	220	100	195	340	80	138	220
16. opening	100	153	200	100	158	260	80	173	280

The individual variations for the first closing movement (interval No. 1) in the test sentences, were very large in all the groups. The reason for this probably lies in the different ways in which the experimental subjects prepared themselves for reading the test sentences. Some subjects were relaxed during the experiment and they moved the velopharynx relatively quickly from a relaxed resting position to closure, so that the commencing movement of closure was relatively short. Other experimental subjects were more tense in anticipation of the test and therefore moved the soft palate up to desired position more slowly. Another factor can be that some subjects did not relax the palate completely between sentences but held it in a kind of "ready" position the whole time.

The individual variations in the final opening movement after the end of every test sentence were much less. This is not unexpected since this movement is passive. When contraction of the soft palate ceases it moves downwards with a speed which may be expected to be rather constant in different people. The differences which occur can be explained partly by some people not allowing the palate sink to the complete and most open resting position but letting it stay in a kind of "ready" position, which is maintained between test sentences.

As shown in the tables, the variations in the time required for the opening and closing movements within the test sentences were generally less than the time required for movements of the beginning or the end of the test sentences. Even here considerable individual variations occur, which reflects the different speeds with which the various experimental subjects pronounce the test sentences or parts of them. In those cases where the opening movement is immediately followed by a closing movement, both intervals have usually occurred at about the same speed. A rapid opening movement is usually followed by an only slightly slower closing movement. However there are exceptions and cases exist with a rapid opening movement followed by a rather slow closing movement. There were only three examples of the opposite, i.e. a slow opening movement followed by a considerably faster closing movement.

Table 9

*Mean duration (msec.) of the movements of the soft palate. Normal cases.
Both sexes.*

	Adults		Children	
	No. of obs.	Mean $\pm$ standard error	No. of obs.	Mean $\pm$ standard error
First closure	79	260 $\pm$ 12	41	210 $\pm$ 13
Opening during speech	205	120 $\pm$ 3	87	110 $\pm$ 4
Closure during speech	205	150 $\pm$ 4	87	140 $\pm$ 5
Last opening	105	170 $\pm$ 5	55	150 $\pm$ 7

Table 9 shows the mean values for the closing movements at the beginning of speech, closing and opening movements under connected speech and opening movements after the conclusion of a test sentence, assembled for adults and children. It is seen that the first closing movement occurs more slowly than a closing movement in the same test sentence. Similarly the final opening movement occurred more slowly than an opening movement within the sentence. On the average, the opening movement occurred more rapidly than the closing movement, both in children and adults. Children had on the average faster movements, but the difference was not significant. The number of observations in children was rather small and had there been more, it might have possible to show a significant difference. However this possible difference between children and adults is probably only slight numerically.

6. The effect of various speeds of speech on the movements of the soft palate

In this investigation, three men and three women were used.

They read the sentences "Mammas fina schal" (Mummy's fine shawl), "Polisen tog boven i badet" (The policeman caught the villain in the bath) and "Gatan var hal av is" (The street was slippery with ice) three times each. The first time they were told to read the sentence at "normal" speed. The second time they were told to read it as slowly as possible without making a pause between individual words. The third time they were told to read the sentences as rapidly as possible.

Results

The mean values from the three test sentences in the six experimental subjects appear in Tables 10, 11 and 12 where the length of the various movement intervals in the soft palate is given in msec.

The tables show that the intervals during which the velopharynx is closed, varied most with varying speeds of speech i.e. low speed of speech gave long closed intervals and high speed of speech gave short closed intervals. It should be pointed out that the lengths of the intervals representing opening or closing movements of the soft palate agreed surprisingly well with the mean duration of the corresponding intervals in adults previously obtained in a larger series.

Table 10

*Duration of different intervals (msec.) with normal, slow and fast speech.
Adults. Test sentence: "Mammas fina schal".*

Interval no.	Movement or position of the soft palate	Rate of speech								
		normal			low			high		
		min.	mean	max.	min.	mean	max.	min.	mean	max.
1	closure	210	260	380	170	440	710	200	270	380
2	half closed	210	370	560	210	490	1170	190	400	940
3	closure	120	210	350	150	250	460	130	180	220
4	closed	150	210	290	440	630	1270	10	90	130
5	opening	120	150	180	80	160	310	90	130	170
6	closure	150	190	250	170	220	290	90	160	200
7	closed	320	440	520	730	780	810			
8	opening	120	180	220	120	170	210			
Silent interval		150	400	640	350	650	940	200	510	600
Voiced sound		1420	1540	1730	2100	2450	3000	840	1050	1340

Table 11

*Duration of different intervals (msec.) with normal, slow and fast speech.
Adults. Test sentence: "Polisen tog boven i badet".*

Interval no.	Movement or position of the soft palate	Rate of speech								
		normal			low			high		
		min.	mean	max.	min.	mean	max.	min.	mean	max.
1	closure	230	260	440	190	300	480			
2	closed	340	430	490	560	670	850			
3	opening	60	120	190	90	160	210	40	80	190
4	closure	90	130	150	120	150	170	60	110	130
5	closed	400	550	750	670	870	1210	130	280	440
6	opening	90	120	170	40	140	190	60	100	170
7	closure	110	160	190	150	200	280	60	120	190
8	closed	560	660	790	730	1100	1600			
9	opening	40	160	230	130	190	230			
Silent interval		210	380	620	230	540	790			
Voiced sound		1580	1970	2580	2240	2990	4140	880	1240	1600

Table 12

*Duration of different intervals (msec.) with normal, slow and fast speech.
Adults. Test sentence: "Gatan var hal av is".*

Interval no.	Movement or position of the soft palate	Rate of speech								
		normal			low			high		
		min.	mean	max.	min.	mean	max.	min.	mean	max.
1	closure	80	250	280	190	360	710		—	
2	closed	230	360	380	190	460	630		—	
3	opening	80	140	210	130	170	200	60	110	150
4	closure	60	140	150	150	170	230	90	130	150
5	closed	980	1200	1460	1350	1860	2520	540	730	1060
6	opening	130	170	270	150	180	220	70	150	210
Silent interval		150	380	480	200	420	980			
Voiced sound		1280	1600	1960	2200	2540	3160	780	944	1160

It also appears that for the movement intervals within the test sentences and the opening movement at the end of every test sentence there was a connection between the length of the interval and the speed of speech, but the changes in the duration of the intervals with changes in speed of speech were very slight, on the average as little as 30 msec.

The variations in the lengths of these intervals were not proportional to variations in speed of speech. The lengths of speech while talking rapidly, "nor-

Table 13

Mean duration (msec.) of different intervals in relation to the movement of the soft palate and the mean duration of the silent interval from the beginning of the first movement to the beginning of voiced sound at various speech rates.
Adults.

	No. of obs.	Normal speech rate	Slow speech	Rapid speech
First closure	10	250	340	—
Opening during speech	24	130	160	100
Closure during speech	24	160	190	130
Last opening	15	170	180	
Silent interval	14	380	550	

mally" and slowly were in the proportions 100–200–300. The mean values for opening movements during rapid, normal and slow speech were, on the other hand, in the proportions 100–130–160. Tab. 13.

An attempt to estimate the distance the palate moves during the opening and closing movements in the test sentences showed that this way was 10–20 % shorter in rapid than in "normal" speech and 10–20 % longer with slow speech than with "normal".

Provided that these estimates are correct, the real mean speed of the opening and closing movements of the palate should be even less affected by speed of speech than would appear from the changes in the lengths of the movement intervals.

During rapid speech, a number of intervals could not be estimated, especially the first and opening movements in every sentence and the closed intervals nearest to these movements. This was so because the experimental subjects did not open the velopharynx between the various test sentences but kept it shut the whole time when they were told to say these sentences as rapidly as possible.

To summarize, this investigation showed that in the six experimental subjects used, the lengths of the opening and closing movements during connected speech increased with statistical significance during slow speech and decreased with statistical significance during rapid speech compared with "normal" speed of speech. However, the changes were not at all proportional to changes in speed of speech and were numerically very slight, on the average 30 msec. (One frame = 20 msec.)

The lengths of the interval from the beginning of movements of the soft palate to the beginning of the sound (the silent interval) and of the first closing movement in a test sentence increased in slow speech approximately

proportionally to the increase in speed of speech. The number of observations of the length of this interval during rapid speech were too few to be able to draw any conclusions.

7. The interval between the beginning of movement of the soft palate and the beginning of sound (the silent interval)

The above diagrams, Fig. 27–32 show that movements of the soft palate begin an appreciable time before any sound is produced. The explanation of this is that the speech organs including the soft palate require time to assume the articulation position required to produce the actual first sound in the test sentences. This interval has been studied for certain consonant complexes by TRUBY & WEGELIUS (1958) and TRUBY (1959). However, it was difficult to determine how long this preparatory articulation required, since they had no exact synchronization between roentgen film and sound recordings.

It is difficult to assess when the occlusive part of a consonant begins from the spectrogram partly because of noise from the film camera. In two of the four test sentences "Mammas fina schal" (Mummy's fine shawl) and "Ingen var vaken vid midnatt" (No one was awake at midnight) which begin with a voiced sound, it is possible with this experimental series to calculate exactly the length of this silent interval between the beginning of palate movement and of voiced sound. The results are shown in the following table.

The silent interval, from the beginning of palatal movement to the beginning of voiced sound i "Mammas fina schal" (Mummy's fine shawl) in msec.

	min.	mean	max.
12 men	100	268	600
14 women	120	400	1120
14 children	130	266	590

It can be seen that there were considerable variations in the values both within and between the groups. It is remarkable that men and children have about the same mean value and an approximately similar variations around the mean. On the other hand, women have a higher mean value and even greater variations. However, the total length of time during which the palate moves and the time during which voiced sound is produced did not vary greatly in the three groups. Thus in this series women showed a deviation from the pattern in the two other groups, the silent interval when saying the test sentence "Mammas fina schal" (Mummy's fine shawl) being considerably longer in women. An emotional factor may be the basis of this different movement pattern in women.

The silent interval from the beginning of palatal movement to the beginning of voiced sound in "Ingen var vaken vid midnatt" (No one was awake at midnight) in msec.

	min.	mean	max.
12 men	200	453	780
13 women	260	438	680
8 children	160	360	720

The mean values in men and women were close to each other, while that in children was somewhat lower. Variations in men and women were of about the same size, while in children they were somewhat greater. Since only eight children were included in the experimental groups, no definite conclusions about the differences between the various groups can be drawn.

In the other two test sentences which begin with [p] or [g], the silent interval could not be determined exactly because of difficulties in identifying the beginning of consonants on the spectrogram. However, if the distance to the beginning of voiced sound in the immediately following vowel is determined the results shown in the following tables were obtained.

The silent interval from the beginning of palatal movements to the beginning of voiced sound in "Gatan var hal av is" (The street was slippery with ice) in msec.

	min.	mean	max.
13 men	20	320	900
14 women	160	370	640
18 children	40	413	1180

The table shows that women on the average required somewhat longer time than men to achieve the desired articulation position for the production of a g-sound, while children require a somewhat longer time than women. However, the differences were not significant. The considerable variations in all the groups are well shown by the accompanying maximum and minimum values.

The silent interval from the beginning of palatal movement to the beginning of voiced sound in "Polisen tog boven i badet" (The policeman caught the villain in the bath) in msec.

	min.	mean	max.
13 men	80	318	420
14 women	120	363	540
15 children	60	335	620

The table shows that there was no great difference between the various groups. As with the other test sentences, variations were large.

In the test sentences "Gatan var hal av is" (The street was slippery with ice) and "Polisen tog boven i badet" (The policeman took the villain in the bath) it was relatively easy to identify and determine the length of the initial consonants g and p on the spectrogram obtained from the sound recording without simultaneous cineradiography.

The lengths of these consonants in the second recording can be expected to be nearly similar to the lengths of the corresponding consonants in the sound recording performed just before with synchronized cineradiography.

If it is assumed that this is correct and the values for lengths of g and p subtracted from the values in the two previous tables, the following results are obtained.

The silent interval between the beginning of palatal movement and the beginning of sound in "Gatan var hal av is" (The street was slippery with ice) in msec.

	min.	mean	max.
men	20	302	880
women	160	337	560
children	40	305	1080

The silent interval between the beginning of palatal movement to the beginning of sound in "Polisen tog boven i badet" (The policeman caught the villain in the bath) in msec.

	min.	mean	max.
men	30	305	420
women	80	329	540
children	60	296	570

As expected there is only a decrease in values of up to 100 msec. but there is no change in the values relative to each other.

8. Correlation between palatal movement-position and the spectrogram

The diagrams of palatal movements in different patients previously described in Chap. I, p. 16 have been correlated for every experimental subject with the Sund spectrogram obtained from speech recorded synchronously with the cineradiography.

The various sound segments have been separated from each other as carefully as possible on the spectrograms and palatal movements and positions during every sound segment have been observed. The results of this correlation between



Fig. 33 illustrates the principles used for separating the different sound segments from each other. With consonants, the occlusive part has been included in the length of the consonant.

palatal position-movement and the corresponding sound as seen on the Sund spectrogram are found below.

A considerable source of error is the difficulty in defining the limits between the various sounds on the Sund spectrogram. In continuous speech the transi-

tion between the various sounds is indistinct and where the boundary can be set between one and the next is always questionable. For this reason, a method has been chosen here for determining the sound limits, which is well-defined, derived from a spectrogram of type visible speech. With this method reproducibility can be guaranteed even if the phonetic correctness of this method can be questioned. The vowels have usually been the easiest to identify. They were assumed to begin and end where the characteristic formants for the vowels have appeared. Similarly the nasal consonants were easy to identify in such a way. The difficulties were greater during identification of unvoiced consonants, mainly because the camera noises lay in the high frequency part of the spectrum where the unvoiced consonants have their main energy. Fig. 33 shows the method used for assessing the boundary between the various sounds in the test sentences.

The error of the method in our determinations from roentgen cinefilms whether or not there was an opening between the soft palate and posterior pharyngeal wall was taken as two frames for every single determination See p. 29. This corresponds to a time of 40 msec., viz. 2 mm. on the Sund spectrogram. Attention was paid to this source of error in the above, i.e. deviations of less than 2 mm. were not accepted as real.

*Correlation between palatal movement-position and the various
sounds in the test sentences*

"Mammas fina schal" ~mammas ~fi:na fa:l (Mummy's fine shawl)

M.

In all the experimental subjects (14 men, 14 women and 21 children) the velopharynx was open while saying the first "m" in "mammas". There were some variations in degree of opening. The individual variations were large.

A.

During the first "a" the soft palate in all the subjects was open, but in the majority of patients there were variations in the opening. This means that this "a" which is between two nasal consonants is nasalized in all the patients as expected.

MM.

The soft palate was also open during the second "m" sound. In the majority, the palate was in a phase of movement between the opening and closing positions while making this sound.

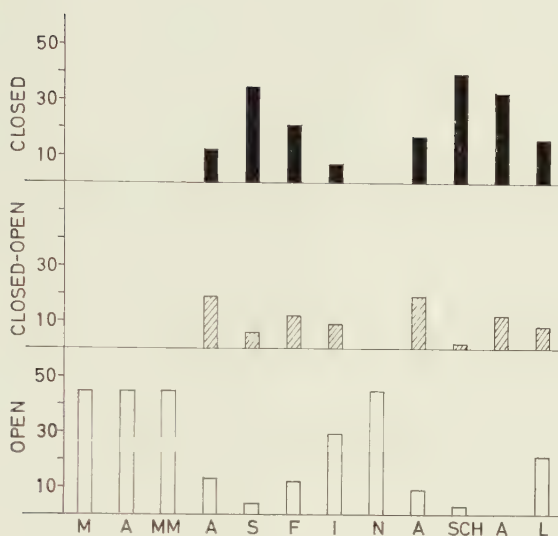


Fig. 34. Diagram showing opening or closure of velopharynx during different sounds in the test sentence "Mammas fina schal", *ˈmammās ˈfi:nə ʃa:l*, (Mummy's fine shawl). The figures refer to the number of test subjects.

A.

In 11 of the experimental subjects the velopharynx was totally closed while saying "a". In a further 19 subjects, velopharyngeal closure was complete during the latter part of "a". In 13 subjects the soft palate was open the whole time while saying "a", implying that in them the greater part of the "a" sound was nasalized.

S.

In most of the subjects the velopharynx was closed during the whole or the greater part of the "s" sound. In five subjects closure was incomplete during the whole of this sound.

F.

In 19 subjects the velopharynx was completely closed during the whole of "f". In the other subjects there was an opening movement during the whole or latter part of the "f" sound.

I.

In four subjects there was complete closure during the whole "i" sound. In all the other subjects the velopharynx was open during the whole or latter part

of the "i" sound. Thus in the great majority there is a nasalization of the "i" sound.

N.

As expected the soft palate in all the experimental subjects was open during the "n" sound. The movement phase of the palate varied. In the majority, the palate was in movement from the opening position to the closing position during the "n" sound.

A.

In ten subjects there was a complete closure of the velopharynx during the whole "a" sound. In the remainder there was an opening during the whole or first part of the "a" sound. Thus in most of the subjects there was a more or less pronounced nasalization of the "a" sound in this position.

SCH

In the great majority of subjects there was a complete velopharyngeal closure during this sound. In two subjects closure was complete during the whole sound and in a further five there was opening during part of the sound.

A

In the majority there was complete closure of the soft palate while saying this "a". A greater or lesser degree of opening during part of this letter occurred in 17 subjects.

L

In 15 subjects there was complete closure during the whole "l" sound. In the others there was an opening during the latter part or in some cases the whole of the "l" sound.

"Polisen tog boven i badet", pu'lisən tu:g 'bu:vən i 'ba:dət, (The policeman caught the villain in the bath)

P

In the great majority the velopharynx was completely closed during the "p" sound. Because it was difficult to determine the length of the "p" sound on the Sund spectrogram, the five cases with a certain opening of the velopharynx during the "p" sound should be assessed extremely carefully. In addition there is also the error in the method of assessing the frame on which velopharyngeal closure is complete. See Chap. II, p. 29. This error, which amounted to about two frames for a single determination, is of course important for a sound like the "p" sound with a short length.

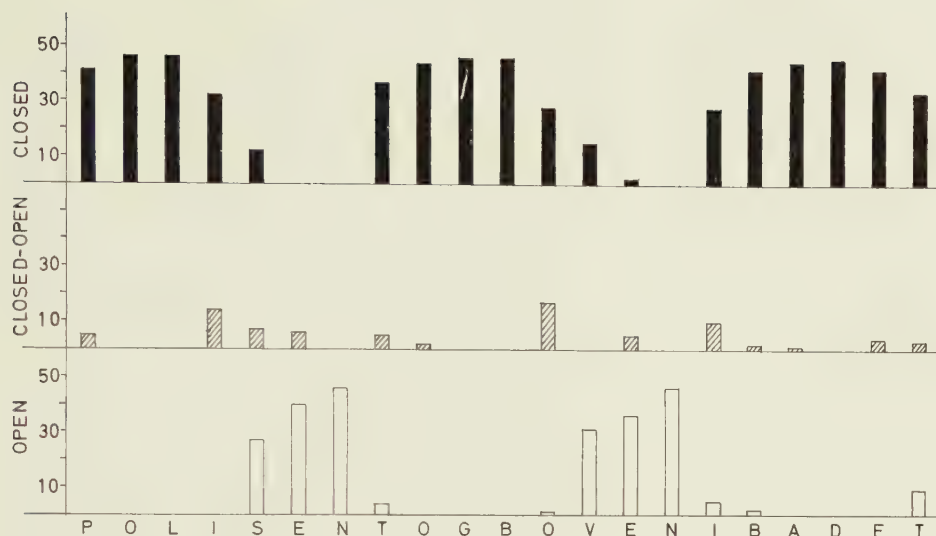


Fig. 35. Diagram showing opening or closure of the velopharynx during the test sentence "Polisen tog boven i badet", *pu'li:sən tu:g 'bu:ven i 'bɑ:dət*, (The policeman caught the villain in the bath). The figures refer to the number of test subjects.

O

The velopharynx in all the subjects was closed during O.

L

In all the subjects, the soft palate was closed during the "l" sound.

I

In 24 subjects the velopharynx was completely closed during the sound "i". In the remainder, during the later part of the "i" sound, there was an opening between the soft palate and posterior pharyngeal wall.

S

Only nine subjects closed the velopharynx completely during the "s" sound. The others had an opening during the later part or the whole of the "s" sound.

E

In seven subjects there was velopharyngeal closure during the first part of the "e" sound and opening during the later part. The other subjects showed an open velopharynx during the whole sound.

N

All the subjects had an opening between the soft palate and the posterior pharyngeal wall during the "n" sound. In the majority the palate was in movement between the opening position and the closing position during this sound.

T

In three subjects the velopharynx was open during the whole "t" sound, in movement between the opening and closing positions. In another seven subjects it was open during the first part of the "t" sound. In the remainder, it was closed during the whole "t" sound.

O

Two subjects had velopharyngeal opening during the first part of the "o" sound. In the remainder, the velopharynx was closed during the whole "o" sound.

G

All the subjects had a closed soft palate during the whole "g" sound.

B

All the subjects had a closed soft palate during the whole "b" sound.

O

The soft palate during the "o" sound was completely closed in 24 subjects. In the other 22, there was a velopharyngeal opening during the later part of the "o" sound.

V

During the "v" sound, the soft palate was quite closed in ten subjects. In the others, there was a varying degree of opening during the whole or later part of the "v" sound.

E

In 36 of the subjects, the velopharynx was open during the whole "e" sound in varying phases of movement. Five subjects had it closed during the first part of the "e" sound but open during the later part.

N

There was opening in the velopharynx during the "n" sound in all the subjects. In the majority the palate was in the moving position between the opening and closing position.

I

In 26 subjects there was complete velopharyngeal closure during the "i" sound. The velopharynx was open during the whole "i" sound in five subjects. In the remaining twelve, the palate was closed during the later part of the "i" sound, but open during the first part.

B

The velopharynx was completely open during the whole of the "b" sound

in two cases. In two more cases opening occurred during the first part of the "b" sound. In the others, it was closed during the whole "b" sound.

A

An opening of the velopharynx occurred in one case during the whole "a" sound.

D

All cases had a closed velopharynx during the whole "d" sound.

E

In one case the velopharynx was open during the whole "e" sound. There was an opening only during the later part of the "e" sound in seven cases. The remainder had a closed velopharynx during the whole "e" sound.

T

In eight cases the velopharynx was open during the whole "t" sound. A further three cases had it open during the later part of the "t" sound. The remainder had it closed during the whole "t" sound. Because of difficulties in limiting the "t" sound on the Sund spectrogram, however, this assessment of the movement or position of the soft palate was uncertain.

"*Gatan var hal av is*", *ˈga:tan va ha:l a:v i:s* (The street was slippery with ice)

G

Eight patients had an opening in the velopharynx during the "g" sound. In one of these patients, however, the soft palate closed during the later part of the "g" sound. In the remainder, the velopharynx was closed during the "g" sound. As previously mentioned, the sources of error are large when delimiting "g".

A

Then was an opening in the velopharynx in 12 patients during the later part of the "a" sound, while in two there was an opening in the first of the "a" sound. In the others it was closed during the whole "a" sound.

T

The velopharynx was completely closed during the whole "t" sound in 12 patients. In the others there was a varying degree of opening during the whole or the later part of the "t" sound.

A

In two subjects the velopharynx was completely closed during the "a" sound. In five patients it was closed during the first part of the "a" sound.

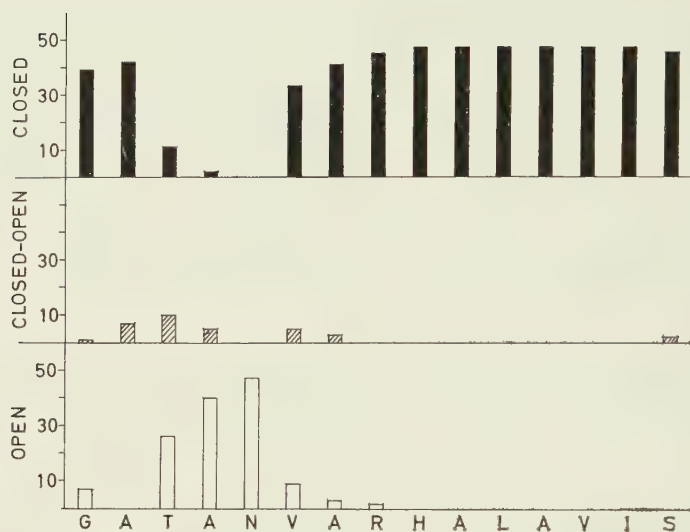


Fig. 36. Diagram showing opening or closure of the velopharynx during the test sentence "Gatan var hal av is", *˘gä:tän vā hā:l ā:v i:s*, (The street was slippery with ice). The figures refer to the number of test subjects.

The remainder had it open during the whole "a" sound to a varying extent and in different phases of movement.

N

All the subjects had the velopharynx open during the "n" sound. Most had movement from the open to the closed position.

V

Nine patients had the velopharynx quite open during the whole "v" sound. It was open during the first and closed during the second part of the "v" sound in five patients. In the remainder it was closed during the whole "v" sound.

A

The velopharynx was quite open during the whole "a" sound in three patients. It was open during a part of the "a" sound in four patients. In the others it was closed the whole time.

R

There was an opening between the posterior pharyngeal wall and the soft palate during the "r" sound in two patients. In the others the velopharynx was closed during the whole "r" sound.

H

The velopharynx was closed during the whole “h” sound in all.

A

In all the velopharynx was closed during the whole “a” sound.

L

During the whole “l” sound the velopharynx was closed in all.

A

The velopharynx in all was closed during the whole “a” sound.

V

In all the velopharynx was closed during the whole “v” sound.

I

During the whole “i” sound the velopharynx was closed in all.

S

The velopharynx was closed during the whole “s” sound, except for one case where it was open during the later part.

“Ingen var vaken vid midnatt”, ~i~j~j~n va ~vaken vi:d ~mi:dnat (No one was awake at midnight)

I

Only in one case was there complete closure during the “i” sound. In one more case there was complete closure during the first part of the “i” sound, with opening during the later part. In all the other cases the velopharynx was open during the whole “i” sound to a varying degree and in different phases of movement.

NG

In all cases the velopharynx was open to varying degrees and phases of movement during the whole “ng” sound.

E

The velopharynx was open in all cases to varying degrees and phases of movement during the whole “e” sound.

N

All cases had the velopharynx open during the “n” sound. The majority had movement phases from the opening position to the closing position.

V

In 15 cases the velopharynx was open during the whole “v” sound. In one case it was open during the first part but closed during the later part of the “v” sound. The remainder had it closed the whole time.

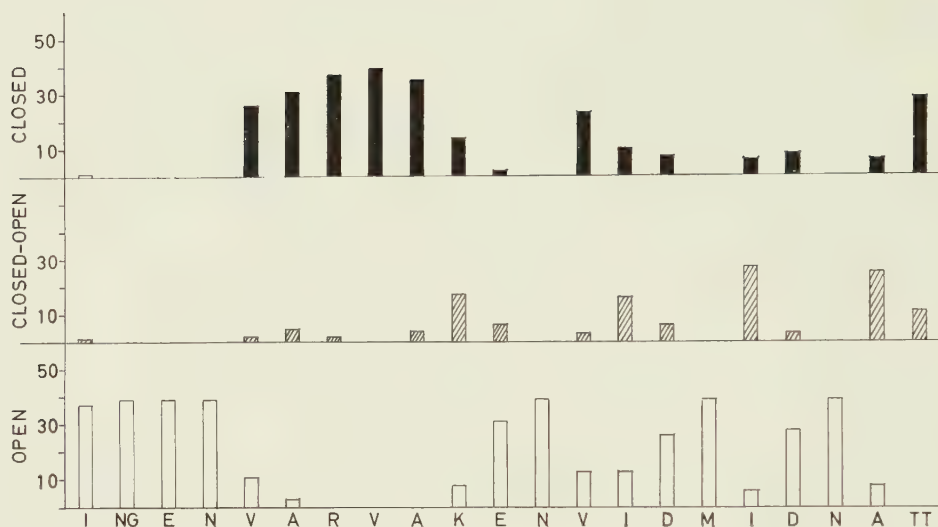


Fig. 37. Diagram showing opening or closure of the velopharynx during the test sentence "Ingen var vaken vid midnatt", *ˈiŋɡən va ˈva:kən vi:d ˈmi:dnɑt*, (No one was awake at midnight). The figures refer to the number of test subjects.

A

The velopharynx was open the whole time in two cases. It was open for the first part of the "a" sound in five cases and closed during the later part. In the other cases it was closed during the whole sound.

R

In two cases the velopharynx was open during the first part of the "r" sound and closed during the later part. All the other cases had it closed during the whole sound.

V

The velopharynx was closed during the whole of the "v" sound in all cases.

A

In six cases the velopharynx was open during the later part of the "a" sound but closed during the first part. It was closed in the other cases during the whole sound.

K

During the whole "k" sound, the velopharynx was open in eight cases. In 14 cases it was closed during the first part of the sound and open during the later part of the sound. In the other cases it was closed the whole time.

E

In three cases the velopharynx was closed during the whole "e" sound. In eight cases it was partly closed during the sound. In the other cases it was open to varying degrees and phases of movement during the whole sound.

N

The velopharynx was open to a varying degree during the "n" sound in all cases. In the majority the palate was in movement between the open and closed positions.

V

In 18 cases the velopharynx was closed during the "v" sound. It was open during the whole sound in 14 cases. In the others it was open during a part of the sound.

I

During the "i" sound the velopharynx was completely closed in six cases. It was open during the whole sound in 13 cases. In the remainder it was closed part of the time.

D

The velopharynx was quite closed during the "d" sound in seven cases. It was quite open during the whole sound in 23 cases. In the remainder it was open part of the time.

M

In all cases the velopharynx was open to a varying degree during the "m" sound.

I

In five cases the velopharynx was open during the whole "i" sound. It was closed during the whole sound in two cases. In the remainder, i.e. the majority, it was closed during part of the sound.

D

The velopharynx was closed during the whole "d" sound in eight cases. It was open during the whole sound in 23 cases and in the remainder open during part of the sound.

N

In all cases the velopharynx was open to varying degrees and phases of movement during the "n" sound.

A

The velopharynx was closed during the whole "a" sound in three cases and

open during the whole sound in two cases. In the remainder it was closed during part of the sound.

TT

In 25 cases the velopharynx was closed during the whole "t" sound. In the remainder it was closed during part of the sound and open during the rest.

The relatively large variations in the position of the palate in relation to sounds recorded on the spectrogram in normal subjects can be seen in the diagrams.

What is most obvious is the varying degree of nasalization of the vowels in connection with the nasal consonants.

In addition it is noteworthy that in several experimental subjects whose speech was interpreted as completely normal, the velopharynx was not closed during the pronunciation of certain consonants, r, k, g, s, f, v and d.

Measurements of the distance between the posterior pharyngeal wall and the soft palate showed that in 14 out of 21 children on one or more occasions there was a distance of more than 1 mm. between the posterior pharyngeal wall and the soft palate corresponding to a consonant in the test sentences. In seven of the 21 children there was no opening during any consonant or at least there was an opening of never more than 1 mm. In the latter cases the coupling area which amounted to less than 5 mm.² may be regarded as being so small that it had no effect on the quality of the sound produced.

In the other cases, the coupling area amounted to as much as 30 mm.², and this must affect the quality of the sound produced. Thus in these cases the patients could not have pronounced the "correct" consonants intended. However the sound which replaced this correct consonant was interpreted by the listeners as being an acceptable equivalent of the desired consonant.

On account of noise from the film camera no definitely assessable spectrograms of the voiceless consonants could be obtained. Thus in this investigation the quality of the illustrations did not allow a sufficiently reliable correlation between the spectrographic patterns of the consonants and the coupling area in the velopharynx.

The same measurements in the 17 men showed that in 12 there was an opening exceeding 1 mm. in the velopharynx while the above consonants were produced. In the other five there was either no opening or one which never exceeded 1 mm.

In six among the 14 women there was an opening exceeding 1 mm. In the other eight there was either no opening or one of less than 1 mm.

Thus in this investigation women have been more careful in their articulation than children or men.

9. Formant analysis of the nasalized vowels [a] and [i]
in relation to the area of the coupling between
the nasal and oral cavities

In order to study the nasalization of the vowels [a] and [i] in connection with various nasal consonants, a special test has been carried out on three experimental subjects. They were asked to read a number of nonsense words during cineradiography and simultaneous sound recording using the technique previously described in Chap. I. The following disyllabic nonsense words were used:

babba ˘ <i>ˈbabba</i>	mamma ˘ <i>ˈmamma</i>	danna ˘ <i>ˈdanna</i>	nabba ˘ <i>ˈnadda</i>
dadda ˘ <i>ˈdadda</i>	nanna ˘ <i>ˈnanna</i>	nagga ˘ <i>ˈnagga</i>	ganna ˘ <i>ˈganna</i>
gagga ˘ <i>ˈgagga</i>	nanga ˘ <i>ˈnangga</i>		ganga ˘ <i>ˈgangga</i>
bibbi ˘ <i>ˈbibbi</i>	mimmi ˘ <i>ˈmimmi</i>	bimmi ˘ <i>ˈbimmi</i>	mibbi ˘ <i>ˈmibbi</i>
diddi ˘ <i>ˈdiddi</i>	ninni ˘ <i>ˈninni</i>	dinni ˘ <i>ˈdinni</i>	niddi ˘ <i>ˈniddi</i>
giggi ˘ <i>ˈgiggi</i>	ningi ˘ <i>ˈninggi</i>	niggi ˘ <i>ˈniggi</i>	ginni ˘ <i>ˈginni</i>
bamma <i>ˈbamma</i>	mabba ˘ <i>ˈmabba</i>		gingi ˘ <i>ˈginggi</i>

The cinefilm obtained was then analyzed in the ordinary way and the distance between the soft palate and posterior pharyngeal wall was measured frame by frame and plotted as a diagram. This diagram was then synchronized with the spectrogram of the recorded speech.

Some suitable cases in which the soft palate had a position varying from complete closure to 30–40 % of complete opening during one and the same vowel were chosen. In these cases spectrograms of amplitude versus frequency, so called sections, were made of the vowel samples using a Kay Electric Sonograph. The procedure of taking spectral sections is described in Chap. I. The time position where the "section" was taken was chosen from a spectrogram which shows time as x-axis and frequency as y-axis and which shows the intensity as blackness. This type of spectrogram is also called visible speech. From this the vowels may be easily identified. A number of "sections" made were representing the nasalized as well as the non-nasalized part of the vowel. The minimal distance between two sections is 5 mm. on the visible speech diagram which corresponds to 37 msec. The time location of the sections cannot be determined exactly. Deviations of 2 mm. from the desired position on the visible speech diagram are possible. This corresponds to almost one frame on the cinefilm, or 15 msec. The diagram of the distance between the soft palate and the posterior pharyngeal wall shows that the difference in

this distance in two consecutive frames can be 15–20 % of the maximum distance. Fig. 14, p. 28. However, with this source of error in mind, it was possible to make a rather careful determination of the distance between the soft palate and the posterior pharyngeal wall corresponding to every section.

Using the diagram obtained in Chap. III, on the relationship between this measured distance and the coupling area between the nasal and oral cavities, it has been possible to determine the coupling area corresponding to each section obtained.

Spectrograms (visible speech) of the previously recorded test sentence "Mammas fina schal" (Mummy's fine shawl) spoken by these experimental subjects were also produced. The vowels [a] and [i] are in this sentence more or less nasalized in connection with [n] in [fi:na]. Sections were made of the nasalized part of the vowels and where possible in the non-nasalized part of the vowel also. The coupling area corresponding to the actual sections was determined as described above.

The coupling areas in these three experimental subjects reached a maximum of 50–60 mm².

Results

In the special test words the nasalization of the vowels was very variable and in some cases up to three sections could be obtained with varying degrees of coupling area between the nasal and oral cavities. The duration of the nasalized part of the vowels in the original test sentences is most often short and usually only one section could be obtained. The changes observed in spectrum from the original test sentences and the special test words agree well, however.

The results obtained with the two vowels [a] and [i] studied in the three experimental subjects are as follows.

The vowel [a]

A characteristic with all three experimental subjects was that as nasalization of the vowel [a] began the formants widened. This was first and most clearly marked in the formants F1 and F2.

There was also a weakening of F1 in comparison with F2, F3 and F4. This weakening of F1 was more pronounced as the coupling area increased.

No definite change in formant frequencies was noticed with the degree of nasalization studied here.

With one of the three experimental subjects a minimum in the spectrum was found at approx. 1500 and 2000 c/s with the second experimental subject at 2000 and 4000 c/s and with the third at 2000, 3000 and 4000 c/s.

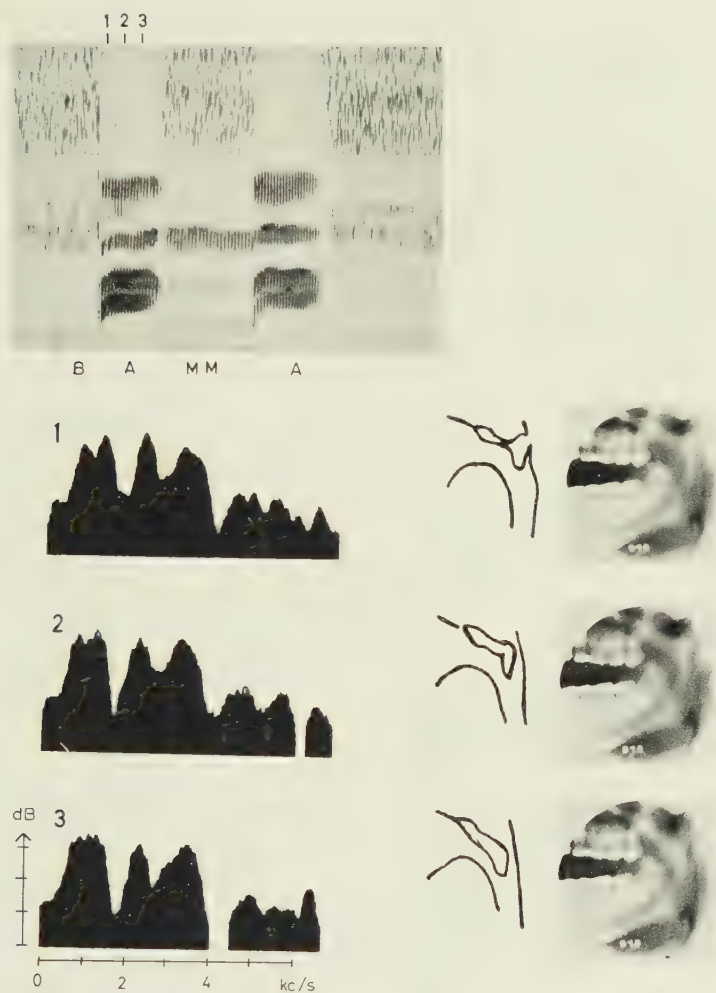


Fig. 38. Three sections of the vowel [a] in bamma [˘bāmmā] taken as close to each other as possible.

- 1) Velopharynx closed.
- 2) Coupling area between nasal and oral cavities c. 15 mm². A widening of F1 and F2 has appeared. Formant frequencies and amplitudes largely unchanged.
A minimum at about 1500 c/s is evident.
- 3) Coupling area 60 mm². Similar to 2) but a minimum at about 4000 c/s has appeared.

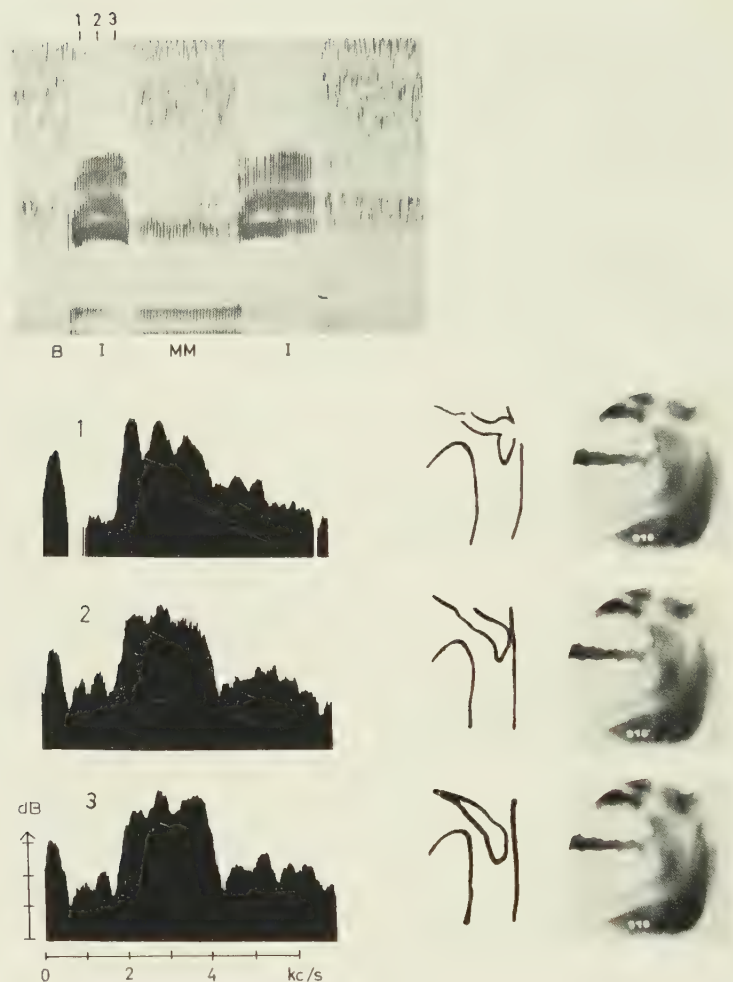


Fig. 39. Three sections of the vowel [i] in bimmi [ˈbimmi] taken as close to each other as possible.

- 1) Velopharynx closed.
- 2) Coupling area between oral and nasal cavity about 15 mm². Widening of F₂, F₃ and F₄. A decrease in level of F₁ in relation to the level of the higher formants. A minimum at about 4000 c/s.
- 3) Coupling area c. 60 mm². Similar to 2) but a minimum at about 1500 c/s has appeared.

The above changes were seen with very small coupling areas (5–10 mm².) between the nasal and oral cavities. The changes appeared more clearly with coupling areas up to 50–60 mm². Fig. 38.

The vowel [i]

During nasalization of this vowel in the three experimental subjects a widening of all the formants was found. This widening increased as the coupling between oral and nasal cavities increased.

A relative decrease in level of the first formant related to the level of second, third and fourth formant was found in all three experimental subjects.

There was no certain change in formant frequency during nasalization.

In one of the experimental subjects a minimum in the spectrum was noticed at approx. 1500 c/s and with another experimental subject at approx. 1500 and 3000 c/s. In the third experimental subject a minimum was found at approx. 1500 and 4000 c/s.

The above changes appeared with very small coupling areas between the nasal and oral cavities of approx. 10 mm². Changes were more marked with increasing coupling areas up to 50–60 mm². Fig. 39.

The changes seen on the spectrograms during this “normal” nasality which did not give a listener the impression of nasality could be summarized as follows.

During nasalization of a vowel from the effect of a *η*-, *n*- or *m*-sound all the formants were widened to a lesser or greater extent. In addition there was a relative weakening of the first formant in relation to the other formants. The formant frequency remained largely unchanged. The spectrum of the vowel [i] displayed minima at 1500, 3000 and 4000 c/s, while in [a] minima were found at 1500, 2000, 3000 and 4000 c/s.

As seen, the changes are small compared with the marked changes in the spectrograms of patients with nasal speech.

10. Studies on simulated nasal speech

In the previous chapter it was seen that the spectrographically observable changes of the vowels [a] and [i] in connection with the nasalization normally found in connected speech in normal subjects were relatively slight compared with the changes seen in operated cleft palate cases with remaining nasal speech.

An investigation was therefore carried out to study the spectrographic changes in the vowels [a], [i] and [ə] in normal subjects who simulated nasal speech.

If this simulation of nasal speech in normal subjects was due to complete or nearly complete opening of the velopharynx, this would anatomically be very similar to the situation in operated cleft palates with pathological speech. The roentgen technique used here made it possible in an easy way to check that this was the case and also determine the size of the opening.

In this investigation four men were used as experimental subjects.

They read the test sentences "Mammas fina schal" (Mummy's fine shawl) and "Polisen tog boven i badet" (The policeman caught the villain in the bath). They simulated and tried to imitate the speech of cleft palate patients with deficient velopharyngeal closure as much as possible. One subject was very successful. Every subject read the sentences twice, once with the nostrils open and once with the nostrils closed with the fingers.

Cineradiography and synchronized sound recording were made using the technique previously described.

Results

Analysis of the roentgen films showed that during speech, two of the experimental subjects held the soft palate almost still in a kind of resting position. It carried out only slight excursions and these movements were very small especially in the experimental subjects who succeeded best in imitating the nasal speech of cleft palate patients. In the other two subjects the palate made sometimes larger and sometimes smaller closing movements.

Using the Kay Electric Sonograph, a spectrogram was produced of the test sentence "Polisen tog boven i badet" (The policeman caught the villain in the bath). In this sentence are [a], [i] and [ə]. Sections were made in the middle of these vowels, and the positions of the sections determined as accurately as possible. The distances between the posterior pharyngeal wall and the soft palate corresponding to the sections obtained, was determined using the synchronized roentgen film. Using the diagram in Chap. III, p. 41 and these distances the coupling areas between the nasal and oral cavities were calculated. Figs. 40, 41 and 42 show examples of sections of the actual vowels in the experimental subjects with simulated nasal speech. Similarly the calculated coupling area between the nasal and oral cavities for every section is given.

When non-nasalized vowels were compared with nasalized vowels from the same experimental subjects, the sections showed important differences.

The changes consisted mainly of a downward displacement of the frequency of the energy maximum at the site of F1, a widening of all the formants and some diminution in amplitude of the high formants compared with F1. There were also antiresonances which appeared as minima in the spectrum.

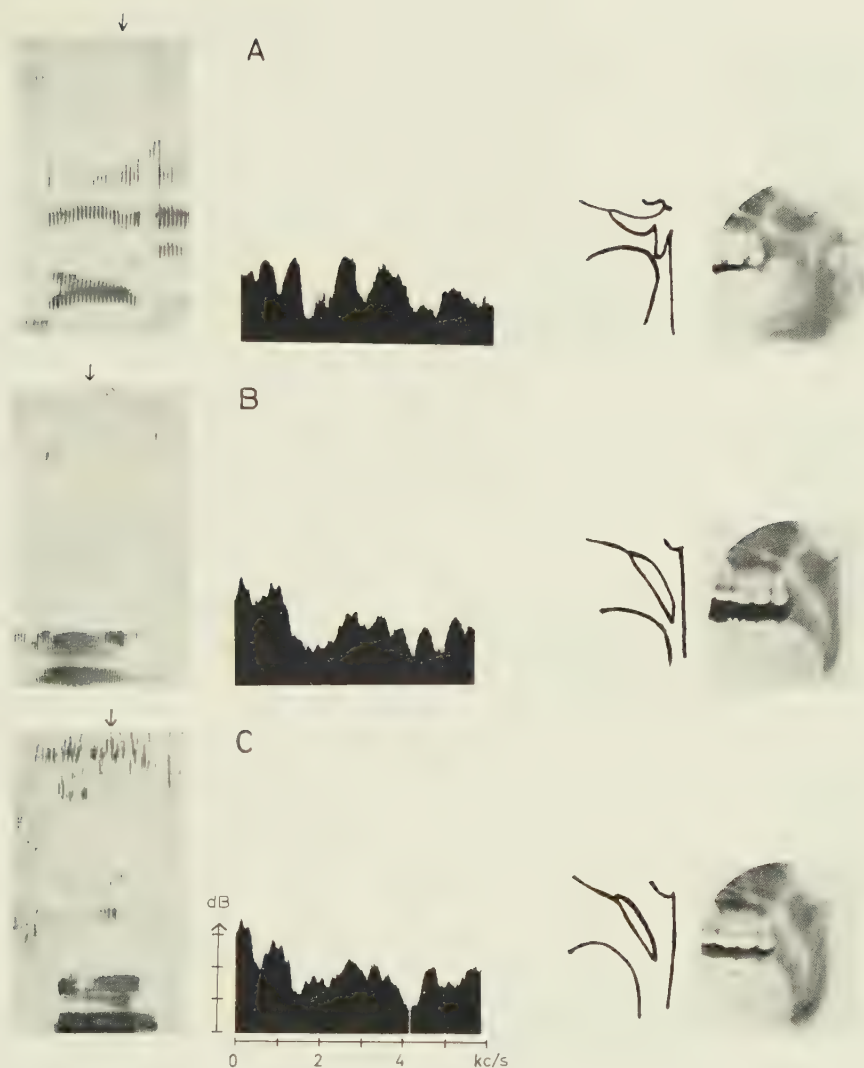


Fig. 40. Section of the vowel [a] in badet ['badət].

A. Normal speech. Velopharynx closed.

B. Simulated nasal speech. Nostrils open. Coupling area 210 mm². Minima at approx. 1500, 2500 and 4000 c/s.

C. Simulated nasal speech. Nostrils closed. Coupling area 230 mm². Spectrum more similar to normal. Minima now at 700, 2500 and 4000 c/s.

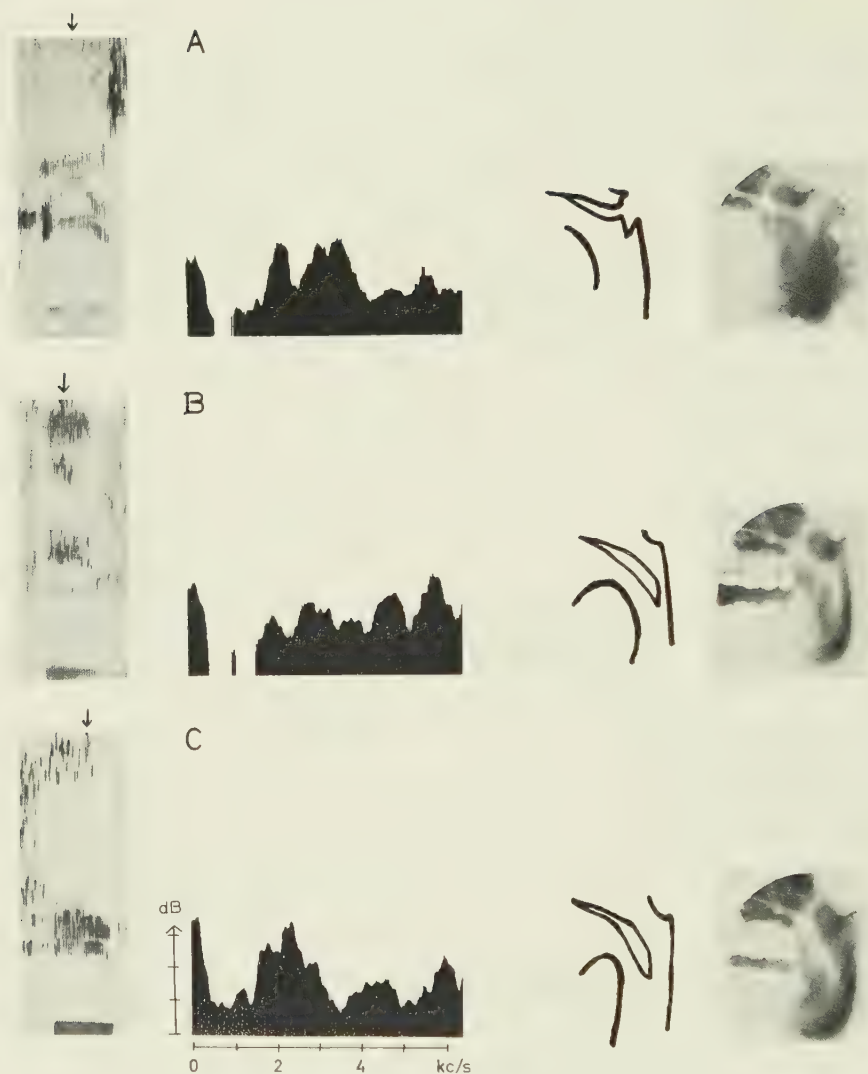


Fig. 41. Sections of the vowel [ɛ] in polisen, [pu'li:sən].

A. Normal speech. Velopharynx closed.

B. Simulated nasal speech. Nostrils open. Coupling area between nasal and oral cavities about 130 mm².

Minima at approx. 1500, 2500 and 3500 c/s.

C. Simulated nasal speech. Nostrils closed. Coupling area 290 mm². Spectrum more similar to normal. Minima now at 1500 and 3500 c/s.

The position of such minima in the frequency spectrum were determined using tracings of the actual spectrograms performed on transparent paper. By projecting such a tracing from a non-nasalized vowel over a tracing of the spectrum from the same vowel nasalized, the position of possible minima with a frequency of approx. 700 c/s and upwards could be identified rather easily. In a few cases it was possible to just notice minima with lower frequency, but it was not possible to determine the frequency with this method in the actual cases. With the various vowels the following minima were observed among the different experimental subjects.

With the vowel [ə] the minima were found at approx. 1500 and 3000 c/s; 1500, 2500 and 4000 c/s; 700 and 3000 c/s; and 3000 c/s in the respective experimental subjects.

The spectrum of the vowel [a] minima were at approx. 1000, 2000 and 4000 c/s; 1500, 2500 and 4000 c/s; 2500 and 4000 c/s; and 1300 and 3000 c/s in the respective experimental subjects.

For the vowel [i] minima were observed at approx. 1500, 2500 and 3500 c/s; 900, 2300 and 3700 c/s; 1000 and 4000 c/s; and 3000 c/s in the respective experimental subjects.

The coupling area between the nasal and oral cavities in three of the experimental subjects varied between 100 mm². and 300 mm². corresponding to the spectrograms (sections) of the different vowels. All three subjects had spectrograms which largely corresponded to those shown in Fig. 40, 41, 42.

The fourth person had a coupling area which for the actual sections was between 10 and 50 mm². In this subject the spectrograms did not correspond to these obtained with the other three subjects but was similar to the spectrograms described in p. 80 with nasalization of vowels in conjunction with nasal consonants.

The above concerns nasal speech with open nostrils (open nasality).

Tests of nasal speech with closed nostrils (closed nasality) were performed in three subjects. The spectrograms of the vowels [a], [i] and [ə] showed less pronounced minima and a less marked widening of the formants than with open nasality. There was no definite change in frequency for the various minima.

However the coupling areas between the nasal and oral cavities with the sections obtained were 10–70 % greater with closed nostrils than with open nostrils.

In two of the experimental subjects minima were recorded in the spectrum from "normal" nasalization of the vowels [a] and [i] in conjunction with nasal consonants.

With the vowel [a] in one subject there were minima at 2000, 3000 and 4000 c/s with "normal" nasalization. With strong nasalization, however, the minima were found at 1500, 2500 and 4000 c/s. This means that the frequency

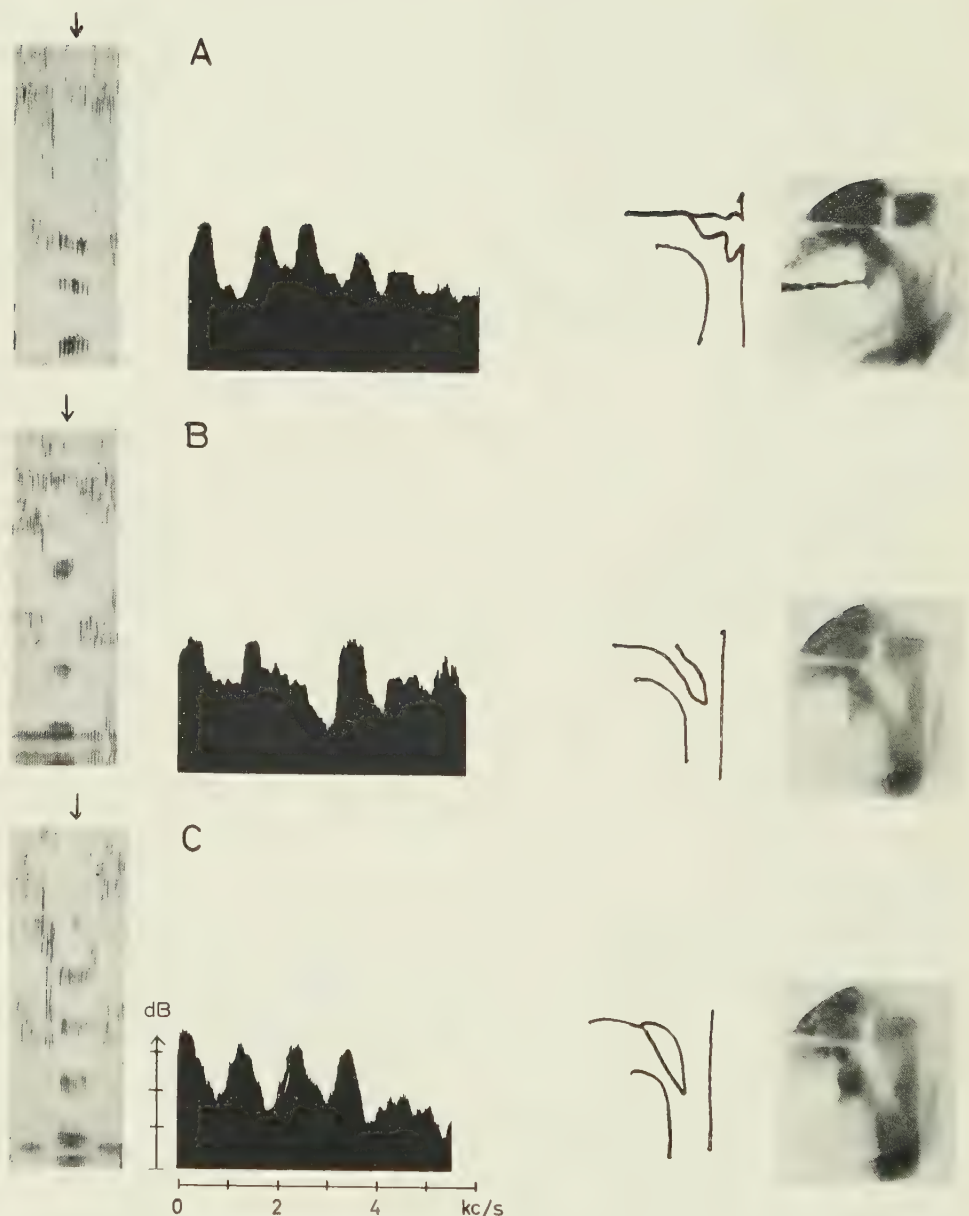


Fig. 42. Sections of the vowel [ə] in badet ['badət].

A. Normal speech. Velopharynx closed.

B. Simulated nasal speech with open nostrils. Coupling area 180 mm². Minima at approx. 1500, 3000 and 4300 c/s. The first formant is displaced downwards in frequency and widened.

C. Simulated nasal speech. Nostrils closed with the fingers. Coupling area 280 mm². Spectrum more similar to normal. Minima less pronounced than in B.

of the minima has been displaced downwards with increased nasalization, i.e. an increase in the coupling area from about 50 mm². to between 130 and 200 mm². In the other subject there was no definite change in the frequency of the minima in association with increase in coupling area.

With the vowel [i] one subject had minima at 1500 and 4000 c/s during normal nasalization. However, with strong nasalization minima were at 900, 2300 and 3700 c/s. In the other subject, minima with normal nasalization were at 1500 and 3000 c/s, and with strong nasalization at 1500, 2500 and 3500 c/s. Thus in both subjects with the vowel [i], an increased coupling between the nasal and oral cavities was accompanied by a downward displacement in the frequency of the minima.

Of course the observed changes cannot always be due to nasality. Formant frequencies and intensities are also affected by the articulation of the adjacent consonants. Nevertheless, the observed changes in the spectrograms during nasality agree well with the observations of previous authors, FANT 1958, FUJIMURA 1960, etc. including analogous studies of synthetic speech.

However, it seems that the nasalization of vowels in "normal" speech, not giving the impression of nasality to a trained listener, produces relatively small changes in the spectrum of the vowels. This is so with coupling areas between nasal and oral cavities from about 10 mm² up to a maximum of 50–60 mm².

Thus it appears that the coupling area between the nasal and oral cavities must be at least 60 mm². in a normal adult for speech to be assessed as nasalized. This corresponds to a minimum distance between the posterior pharyngeal wall and soft palate of approx. 4 mm. on a cinefilm in lateral projection.

The method described here makes it possible in experimental subjects and patients to study changes in the spectrogram during connected speech in relation to the coupling area between the nasal and oral cavities. For every section obtained a corresponding coupling area can be determined with a relatively large degree of accuracy. The studies presented here may be considered as examples of the usefulness of the method.

Summary

Chapter I describes the methods developed for high speed cineradiographic studies of the speech organs during connected speech, using a roentgen image amplifier and 35 mm. film camera.

The sound produced has been recorded on a high fidelity tape recorder simultaneously with the taking of the cinefilm.

By using a special 48 channel sound spectrometer constructed by Sund the speech recorded has been analysed according to the visible speech method. With this spectrometer it is possible to obtain visible speech recordings of any desired length of speech.

By means of a special synchronizing device we have been able to correlate each frame of the roentgen cinefilm exactly in time with the sound produced as seen on the visible speech.

Using this method valuable information concerning speech production can be obtained in normal cases and in cleft palate cases before and after operation.

Chapter II describes studies of the reliability of the methods used.

In Chapter III rectilinear simultaneous tomography was used to study the anatomy of the velopharynx in experimental subjects during articulation. The posterior surface of the soft palate was seen to be approximately flat and parallel with the frontal plane for a distance of about 1 cm. on either side of the midline. Similarly the posterior pharyngeal wall is flat for a corresponding distance. These structures can therefore conveniently be studied on a roentgen cinefilm in lateral projection.

When comparative assessment of the same patient is made with simultaneous tomography and cineradiography with our method, cineradiography is seen to be a safe method of judging whether velopharyngeal closure exists or not, both in normal subjects and in patients operated with a pharyngeal flap.

For acoustic calculations of nasality it is of great importance to know the cross-sectional area of the coupling between the nasal and oral cavities as exactly as possible. During articulation of single sustained sounds this area can be reproduced with relatively good accuracy using transversal tomography. The cross-sectional area was found to be mainly elliptical. The variations of

this area during various articulation positions were observed in ten normal experimental subjects. The cross-sectional area was seen to be a linear function of its sagittal major axis. The length of the sagittal major axis can be obtained not only from the transversal tomogram but also from a picture of the velopharyngeal region in lateral projection, e.g. the roentgen cinefilms taken by us. In this way it is possible with the help of this measurement obtained from the cinefilms to follow the variations in size of the coupling area between the nasal and oral cavities during connected speech.

In Chapter IV cineradiographic and sound spectrographic studies of a normal series are presented. The experimental subjects underwent a listening test, in which an assessment of their nasality was included. Slight or moderate open nasality was assessed in 14 out of 26 children on some occasion. This illustrates the difficulties in determining what is normal in children of these ages. The result implies that nasality is a normal occurrence in speech of over one half of these children.

The movements of the soft palate while four test sentences were being read was recorded by cineradiography in adult men and women and in children aged 6–8 years. The movement pattern between the various groups of the series agrees very well. It implies that the soft palate largely follows a rather constant pattern of movements during the pronunciation of these test sentences.

The mean time required for opening and closing of the velopharynx in the test sentences in relation to nasal consonants amounts to about 120 and 150 msec. respectively while the first closing movement in every test sentence shows greater individual variations.

The speeds of the opening and closing movements of the soft palate in the test sentences are only slightly affected by the varying speeds of speech. However the first closing movement is approximately proportional to the speed of speech.

The silent interval between the beginning of palatal movement and the production of sound as seen on the synchronized Sund spectrogram was determined. It amounts to between 300 and 450 msec. with large individual variations.

By synchronizing the Sund spectrogram with the movement diagrams for the soft palate, it has been possible to determine the movements and positions of the soft palate during the various sound segments in the test sentences. It has been found that about two thirds of the men and children in the series and one third of the women had a coupling area in the velopharynx exceeding 10 mm^2 , on some occasion while pronouncing unvoiced consonants. The interpretation was that the experimental subjects did not pronounce the desired

consonants, but similar sounds which were accepted as satisfactory by the listener.

The "normal" nasalization of the vowels [a] and [i] in association with nasal consonants was studied in relation to the coupling area between the nasal and oral cavities in three experimental subjects. The changes in the spectrogram which are relatively small can already be seen with a coupling area of about 10 mm². and increase successively to a coupling area of 50–60 mm²., which is the largest observed in these experiments. In general, the changes consist of a widening of the formants and a relative weakening of the first formant compared with the higher formants. In addition antiresonances appear and are seen as minima in the spectra of the vowels.

The spectrographic changes described above are not at all so marked as those in cleft palate patients with residual nasal speech following operation. In order to be able to study these conditions more closely, four normal men were instructed to mimic the nasal speech of cleft palate patients as much as possible. Synchronized cineradiographic and sound recordings were made at the same time. Coupling areas corresponding to sections of the vowels [a], [i] and [ə] amounted to between 100 and 280 mm². There were much greater changes in the spectrograms than those found with "normal" nasalization, appearing as marked antiresonances, seen as minima in the vowel spectra. There was also a widening of the formants and a downward displacement of the first formant. During nasal speech with closed nostrils the spectrograms appeared more normal even though the coupling area between the nasal and oral cavities was greater in these cases than during nasal speech with open nostrils.

The results mentioned above may be considered good examples of the utility of our method for studying connected speech as seen on a sound spectrogram in relation to the physiological changes of the speech organs, derived from roentgen cinefilms in lateral projection. In the present work studies were limited to the functions of the soft palate and velopharynx. This was done to limit the size of the project. A special difficulty with an investigation of this kind is the enormous amount of information derived from every short recording of only a few seconds. Analysis of this information is necessarily very time-consuming. In the future the speech organs in their entirety can of course be studied by this technique. By combining tomographic and cineradiographic methods the cross-sectional areas at various levels of the speech organs can be determined much more accurately than before. The method opens up great possibilities for continuous studies of the physiological changes in the speech organs in relation to the connected speech produced.

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